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Abstract

Results are presented from an experimental evaluation of IM7/977-2, IM7/F655, and T800/F3900. Data presented include ply-level (unidirectional laminate) strengths and moduli, unnotched and notched (open-hole) tension and compression properties of quasi-isotropic laminates, and compression-after-impact strengths. These data are compared with properties of other toughened (IM7/8551-7 and IM6/1808I) and brittle (T300/5208) graphite/epoxy materials. The IM7/977-2, IM7/F655, and T800/F3900 materials are substantially stronger and more damage tolerant than widely used first-generation composite materials such as T300/5208. The T800/F3900 outperforms IM7/977-2 and IM7/F655 materials in tolerance to projectile impacts. Compression-after-impact strengths were found to be dependent on impactor velocity for a given impact energy. The open-hole compression properties of all three materials are degraded by the combination of heat and moisture.

Introduction

The brittle behavior of graphite/epoxy composites remains a major barrier to expanding their use in aircraft primary structures. Drilled-holes or impact-induced delamination can severely degrade the performance of these materials, particularly in compression. As a result, structural design utilizing composites is based on very conservative design allowables. There is a strong need to develop composite materials which resist delamination and are more tolerant of damage.

High-strain fibers and toughened epoxy resins have been developed in order to improve the performance of graphite/epoxy composites (refs. 1 and 2). Certain bismaleimide (BMI) resins have been modified to increase toughness. Three additional toughened matrix materials, 977-2, F655(BMI), and F3900, are now commercially available as prepregs incorporating high-strain graphite fibers. These new materials have the potential to offer substantially better structural performance than earlier brittle graphite/epoxy composites such as Thornel T300/Narmco 5208 (T300/5208) which is in widespread use.

Results are presented from an experimental evaluation of IM7/977-2, IM7/F655, and T800/F3900. Data presented include ply-level (unidirectional laminate) strengths and moduli, unnotched and notched (open-hole) tension and compression properties of quasi-isotropic laminates, and compression-after-impact strengths. These data are compared with properties of other toughened and brittle graphite/epoxy systems. All laminate fabrication, specimen preparation, and testing were performed at the Langley Research Center.

Materials

The IM7/977-2 (also designated by the supplier as HYE-1377-2T) material was obtained from ICI Fiberite. Hercules IM7 is a graphite fiber with a high failure strain (about 1.6 percent strain at failure), and the 977-2 is a two-phase toughened epoxy. Both the IM7/F655 (also designated HX1539) and T800/F3900 (also designated T800/3900-2 or Torayca P2302) were obtained from Hexcel. Torayca T800 is a graphite fiber with a high failure strain. The F655 is a two-phase toughened bismaleimide (BMI) resin. Conventional, nontoughened BMI resins offer improved high-temperature capabilities but have lower failure strain than epoxy resins such as Narmco 5208. The F3900 resin uses a different toughening approach and combines a toughened epoxy with small elastomeric particles which form a compliant interface or interleaf between fiber plies to resist impact damage and delamination. Table 1 lists composite prepreg information supplied by the manufacturers.

To fabricate laminates from tape prepreg, standard bagging procedures (ref. 3) were used. The manufacturers' recommended cure cycles for each material were followed. The cure cycle for 977-2, shown in figure 1, contains a hold on the temperature ramp, which is often used when processing materials to allow more time for compaction and/or removal of solvents. The cure cycle for F655 (fig. 2) also contains this hold and requires an additional 16 hr postcure at 450°F. The cycle used for F3900 (fig. 3) utilizes a constant ramp-up in temperature which is preferred by users for ease of processing. Each laminate was ultrasonically inspected after curing and all were determined to be of good quality. Fiber volume

fractions were determined following the procedure of ASTM D3171-76. (See ref. 4.)

Test Specimens

Unidirectional $[0]_8$, $[45/-45]_{2s}$, and quasi-isotropic $[45/0/-45/90]_{5s}$ laminates were fabricated from each material and machined into specimens for the test matrix shown in table 2. Specimen configurations are shown in figure 4. With the exception of the short-block compression specimen, a Langley Research Center configuration, the specimens are similar to those recommended in references 3 and 5. Three to five replicate specimens were tested in each configuration to obtain average values for various inplane mechanical properties. Strain gauges were installed on each specimen as recommended in references 3 and 5.

Test Procedures

Environmental Conditioning

Most tests were performed at room temperature and the specimens contained only ambient moisture from exposure to laboratory and shop environments. This condition is identified as "room temperature, dry" (RTD). Certain specimens were tested in a wet condition at 180°F. This condition is identified as "hot, wet" (HW). A heating chamber attached to the test machine regulated the temperature of the specimen and test fixture for these tests. Specimen temperature was measured with a thermocouple (adhesively bonded to the specimen surface) throughout the testing. Specimens were conditioned by immersing them for 45 days in 160°F water. Compression-after-impact specimens were immersed after being impacted. To measure the amount of moisture absorbed, small coupons (approximately 1 in. square) were cut from laminates and weighed at the ambient moisture condition. They were then placed in the hot water along with the test specimens, and their weights were again recorded after 45 days of immersion. Measurements indicated that the IM7/977-2 absorbed 0.74 percent moisture by weight, whereas the IM7/F655 and T800/F3900 absorbed 0.90 and 0.68 percent, respectively. Hot, wet specimens were instrumented with strain gauges immediately after removal from the water and were usually tested within 1 to 2 hr.

Tension, Compression, and Shear Tests of 0°, 90°, and ±45° Laminates

All tension specimens (fig. 4(a)) were tested in a 55-kip electronic servo-hydraulic testing machine with hydraulic pressure actuated grips. The 0° tension specimens had fiberglass tabs, whereas the ±45° and 90° specimens were gripped with Lexan film to avoid damage from the knurled grip surfaces. All tension tests were performed at a displacement rate of 0.05 in/min, and an IBM-PC-based data acquisition system recorded load and strains throughout the tests. Unidirectional compression tests utilized a short-block specimen (fig. 4(b)) and the fixture shown in figure 5. This fixture applies an end load to the specimen while clamping the ends to eliminate "brooming" failures. Compression specimens were tested in a 120-kip hydraulic testing machine at a load rate of 10 kips/min with strains recorded throughout loading.

Tension and Compression Tests of Quasi-Isotropic Specimens

Unnotched and notched (open-hole) quasi-isotropic tension and compression specimen configurations are shown in figures 4(b), (c), (d), and (e). Baseline (unnotched) compression specimens were tested in the short-block fixture. Notched specimens were mounted in a test fixture which not only clamps the ends in a similar manner but also provides knife-edge support along the sides to help prevent buckling. Reference 3 recommends a 10- by 3-in. specimen for unnotched compression testing, but the short-block fixture has been found to produce higher strength results (ref. 1). All quasi-isotropic compression specimens were tested in a 120-kip testing machine and loaded at a rate of 20 kips/min. Notched and unnotched tension specimens were gripped using Lexan film and tested in the same machine as the ply-level specimens at a displacement rate of 0.05 in/min.

Compression-After-Impact Tests

Compression-after-impact tests were performed on 40-ply quasi-isotropic specimens (fig. 4(f)) which were impacted with an aluminum projectile fired from an air gun. The low-velocity air gun apparatus, developed at the Langley Research Center, is shown in figure 6. It consists of a machine gun barrel with a 0.50-in. bore with a solenoid valve connected to a pressure-regulated air supply. Two pairs of light-emitting and light-detecting diodes at the end of the gun are connected to a time recorder to measure projectile velocity. Projectile velocity is varied by adjusting the air pressure. The projectiles used are aluminum spheres with a weight of 0.0065 lb.

For the impact, the specimen was supported in the compression test fixture shown in figure 7. Specimens were impacted at two different energy levels, 20 and 30 ft-lb. A velocity of 443 ft/sec is required to produce an impact energy of 20 ft-lb. For a 30 ft-lb impact energy, a velocity of 540 ft/sec is required.

In addition, one specimen was impacted at 30 ft-lb with the drop weight apparatus and support fixture described in reference 3.

After the impact event, the tests were performed as prescribed in references 3 and 5. The specimens were ultrasonically inspected to determine the internal damage. Then strain gauges were added and the specimens were installed in the apparatus shown in figure 7, which clamps the ends of the specimens to prevent brooming and provides knife-edge support to the sides to prevent buckling. Compression loading was applied at a rate of 20 kips/min and strains were recorded throughout the testing.

Results and Discussion

Test data for all individual specimens of the three materials are given in tables 3 through 11. The tables also include average values and standard deviations for the various engineering properties. Figures 8, 9, and 10 show typical stress-strain plots for the three materials. Figures 11 through 16 show selected property values for the various specimen configurations. Also, for comparison purposes, these figures include property values (data from ref. 1) for three other graphite/epoxy materials: IM7/8551-7, IM6/1808I, and T300/5208. IM7 and IM6 are both high-strain graphite fibers, and 8551-7 and 1808I are both toughened epoxies. The 8551-7 resin, like the F3900 system, combines a toughened epoxy and small elastomeric particles, whereas the 1808I incorporates a thin (1-mil) thermoplastic film applied to one side of the prepreg tape. Sometimes denoted as a first-generation composite material, T300/5208 consists of low-strain graphite fibers and a brittle epoxy resin and has been extensively used in aircraft secondary structures.

Ply-Level Properties of $[0]_8$, $[90]_8$, and $[45/-45]_{2s}$ Laminates

Data from tests of 0° laminates of IM7/977-2, IM7/F655, and T800/F3900 are listed in tables 3 and 4. The unidirectional tension tests primarily indicate fiber performance. The laminates of these three materials have similar volume fractions, and as expected, the two materials incorporating IM7 fibers have nearly identical values of tensile strength (365–370 ksi) and modulus (20–21 Msi (million pounds per inch^2)). For comparison purposes, 0° tension strength and modulus values for 0° laminates are plotted in figure 11 along with data from IM7/8551-7, IM6/1808I, and T300/5208. Although all these materials have essentially the same modulus, laminates incorporating high-strain fibers have the highest ultimate strength.

Unidirectional compression testing was performed to obtain values of modulus and Poisson's ratio. The short-block configuration does not produce meaningful values of unidirectional compression strength due to longitudinal splitting failures at the ends of the specimen. All unidirectional compression specimens failed in this manner. Strength values listed in table 4, therefore, should not be considered valid indicators of the unidirectional compressive strength of these materials. Values of modulus and Poisson's ratio, however, are valid as they are based on strain measurements well below the stress at which splitting occurs. As expected, these 0° elastic property values are nearly identical for the three new materials for both tensile and compressive loading.

Data from the tension tests for 90° laminates are listed in table 5 and average values of tensile strength and modulus are plotted for the six materials in figure 12. As the load is introduced in the direction normal to the fibers, this test is primarily a measure of resin performance. Although the new materials have similar values of modulus, the IM7/F655 material developed only one half the ultimate strength of the materials combining IM7 fibers and toughened epoxy matrices. This result was expected because bismaleimides tend to have lower failure strain. As shown in figure 12, materials constructed with 977-2, F3900, and 8551-7 resins exhibit similar strength and stiffness performance in this test.

The tension test (ref. 4) for ±45° laminates is used to obtain shear modulus (G_{12}) values, and test values depend on both matrix material and fiber/matrix interactions. Data from these tests are given in table 6, and a comparison of extensional strength and modulus is made in figure 13 for the six materials. In these tests, the materials which are more compliant typically have a higher ultimate strength. Data in figure 13 show that the newer toughened systems substantially outperform (by 45–90 percent) the T300/5208, which has the lowest strength and highest modulus. It is important to note that although this test yields a valid elastic shear modulus value, measurements must be done at low loads when the fibers are oriented at ±45°. As higher loads are applied, stress-strain response of the laminate becomes nonlinear. The laminate is then in a state of combined stress rather than pure shear, and therefore a shear failure strength is not obtained from this test.

Properties of Unnotched and Notched Quasi-Isotropic Laminates

Tension data for unnotched quasi-isotropic laminates are shown in table 7 for the three materials

tested in this investigation. Nearly identical ultimate strengths and moduli were obtained for the three materials. Test data for notched (open-hole) tension specimens are given in table 8, and both notched and unnotched results for the six materials are shown in figure 14. It is important to note that the notched strengths are all based on the gross specimen cross-sectional area. All the composites which combine high-strain fibers with toughened resin matrices performed (30–75 percent) better than the T300/5208 system, with the IM7/F655 having the highest open-hole tension strength.

Compression properties for unnotched and notched laminates of IM7/977-2, IM7/F655, and T800/F3900 are given in tables 9 and 10, respectively. The short-block compression test produces valid strength information from these relatively thick 40-ply quasi-isotropic specimens. Figure 15 shows average values of strengths of unnotched and notched (open-hole) specimens and includes comparative data for the other toughened and first-generation composites. Unnotched strength of the materials made with high-strain fibers range from 90 to 100 ksi, about 25 percent higher than the low-strain T300/5208 material. The IM7/F655 has the highest strength in this comparison, the higher stiffness resin likely preventing premature out-of-plane fiber distortion. Data in figure 15 show that although the composites incorporating high-strain fibers and toughened resin have high unnotched compression strengths, when notched they are degraded to roughly the same strength (34–40 ksi) as the first generation T300/5208.

Hot, wet conditions significantly reduce the notched compression strength of all three materials tested in this study (table 10 and fig. 15); again the F655 resin composite suffered slightly less strength reduction under these conditions. This strength advantage at elevated temperature evidenced by the bismaleimide resin is expected to become greater at temperatures higher than the 180°F used in these tests.

Compression-After-Impact Results

Test results for the quasi-isotropic panels of this investigation are given in table 11. Average values of failure strength are shown in figure 16 along with previous data for IM7/8551-7, IM6/1808I, and T300/5208. Three toughened epoxy matrix materials (T800/F3900, IM7/8551-7, and IM6/1808I) offer substantial (65–100 percent) increases in impacted compression strength compared with the first-generation T300/5208. These results were expected because of the use of high-strain fibers and matrix. It was also anticipated that the BMI (IM7/F655) would not perform well after impact damage was induced because of the low failure strain matrix. However, the compression strength of the IM7/977-2 material after air gun impact was totally unexpected. This material at an impact of 30 ft-lb (test 3) performed only slightly better than the low failure strain systems IM7/F655 and T300/5208. None of the three new materials studied were strongly affected by hot, wet conditioning.

Because the air gun apparatus used at the Langley Research Center causes more damage (refs. 1 and 2) than the conventional drop weight impactor widely used by industry (ref. 3), one specimen from each material in this investigation was impacted with a drop weight for comparison purposes. The drop weight impact energy corresponds to 1500 in-lb/in., a parameter widely used in evaluating composite materials. As seen in figure 16 (tests 3 and 5) for a given impact energy, specimens impacted with a slow moving drop weight impactor developed higher residual compression strengths than those impacted with a fast moving air gun projectile. At a drop weight impact of 30 ft-lb, laminates made with 977-2 resin have the same failure strengths as those made with F3900, although 8551-7 (ref. 6) performs somewhat better. The composite materials evaluated exhibit nonuniform differences in performance with the two methods of impact. IM7/977-2 has a 35-percent lower strength with the air gun compared with that for the drop weight; IM7/F655 differs by 25 percent, and T800/F3900 exhibits a difference of only 8 percent.

References 2 and 7 offer an explanation for the difference in behavior with the two methods of impact, and figure 17 is taken from reference 2. When a laminate is struck by a fast moving projectile (540 ft/sec), it undergoes a very local deformation of brief duration. This local deformation places the specimen in a state of transverse shear stress, which causes delamination if it exceeds the interlaminar shear strength of the composite. The dropped weight impact, however, is a much slower event in that the impactor is traveling at about 14 ft/sec at the same impact energy level. This slow speed may allow the specimen to deform globally as a plate, spreading the deformation over a larger area and therefore reducing the transverse shear stresses.

A limited investigation was performed to study these phenomena. Tests were performed with the multipoint shear fixture described in reference 7, which was designed to simulate in two dimensions the deformation which occurs under a projectile impact. Four specimens 1 in. wide and 4 in. long, each of IM7/977-2, IM7/8551-7, and AS4/3501-6, were tested in the shear fixture, and their average load

displacement curves are plotted in figure 18. IM7/977-2 and IM7/8551-7 were tested because they displayed a dramatic difference in compression strength after projectile impact by the air gun. AS4/3501-6 is a brittle material similar in compression-after-impact strength to T300/5208 and was used because there was an insufficient quantity of T300/5208 available. Figure 18 shows that the AS4/3501-6 specimens failed at about half the load carried by the IM7/8551-7 specimens. However, the IM7/977-2 laminate failed at higher loads than the IM7/8551-7 in this test; this was an unexpected finding because the materials reported in reference 5 that reached high loads were in all cases more tolerant to air-gun impact damage.

The multipoint shear tests did not explain the measured difference in compression strength of IM7/977-2 and IM7/8551-7 after projectile impact by the air gun. However, the compression-after-impact data show, that over the range of impact energies and impactor velocities examined, the materials which perform best have an energy-absorbing interleaf between plies combined with a toughened epoxy matrix. Both F3900 and 8551-7 contain small elastomeric particles, while 1808I has a thermoplastic interleaf (ref. 2). This interleaf material and the toughened matrix possibly serve to halt or delay delaminations within the laminates.

Conclusions

Three composite materials made of toughened resin matrix and high-strain graphite fibers were tested to obtain ply-level and quasi-isotropic laminate engineering properties. Tension and compression stiffness and strength data were generated for unnotched and notched (open-hole) specimens. Composite panels were impacted at energy levels of 20 and 30 ft-lb and residual compression strengths were determined. The effects of elevated temperature and moisture on compression strength of notched and impacted specimens were investigated. The results of the experimental investigation support the following conclusions:

1. The IM7/977-2, IM7/F655, and T800/F3900 materials are substantially stronger and more impact damage tolerant than widely used first-generation composite materials such as T300/5208.
2. The IM7/977-2 and T800/F3900 offer significant and similar increases in residual strength over untoughened materials when damaged by a slow moving impactor. The T800/F3900 outperforms IM7/977-2 and IM7/F655 materials in tolerance to projectile impact.
3. The notched compression properties of all three materials are degraded by the combination of heat and moisture.
4. Compression-after-impact strength is dependent on impactor velocity for a given impact energy. These velocity-dependent strength differences were not uniform from one material to another in this investigation.
5. A combination of toughened matrix resin and a compliant interleaf between plies is required to produce good damage tolerance over a range of impact energies and impactor velocities.

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Table 1. Composite Prepreg Information

IM7/977-2:
- Fiberite HYE-1377-2T 12-in-wide tape
- Areal weight of 145 g/m^2
- Wet resin content of 38 percent, by weight
- Volatile content < 3 percent
- 350°F cure temperature
- Lot C89-0060, manufactured 2/14/89

IM7/F655:
- Hexcel T9A145 HX1539 12-in-wide tape
- Areal weight of 146 g/m^2
- Wet resin content of 33 percent, by weight
- Volatile content < 2 percent
- 375°F cure temperature
- B.O. #22560, manufactured 5/19/89

T800/F3900:
- Hexcel F3900 12-in-wide tape
- Areal weight of 145 g/m^2
- Wet resin content 35 percent, by weight
- 350°F cure temperature

Table 2. Test Matrix

Laminate ply orientation	Loading direction	Test condition (a)	Quantity	Specimen drawing, see figure—
$[0]_8$	0° tension	RTD, unnotched	5	4(a)
$[90]_8$	90° tension	RTD, unnotched	5	4(a)
$[0]_{16}$	0° compression	RTD, unnotched	5	4(b)
$[45/-45]_{2s}$	±45° tension	RTD, unnotched	5	4(a)
$[45/0/-45/90]_{2s}$	Tension	RTD, unnotched	5	4(c)
$[45/0/-45/90]_{2s}$	Tension	RTD, 0.25-in. hole	3	4(d)
$[45/0/-45/90]_{2s}$	Tension	RTD, 0.50-in. hole	3	4(d)
$[45/0/-45/90]_{5s}$	Compression	RTD, unnotched	5	4(b)
$[45/0/-45/90]_{5s}$	Compression	RTD, 0.25-in. hole	3	4(e)
$[45/0/-45/90]_{5s}$	Compression	RTD, 0.50-in. hole	3	4(e)
$[45/0/-45/90]_{5s}$	Compression	RTD, 1.00-in. hole	3	4(e)
$[45/0/-45/90]_{5s}$	Compression	HW, 0.25-in. hole	3	4(e)
$[45/0/-45/90]_{5s}$	Compression	RTD, 1000 in-lb/in., AG	3	4(f)
$[45/0/-45/90]_{5s}$	Compression	RTD, 1500 in-lb/in., AG	3	4(f)
$[45/0/-45/90]_{5s}$	Compression	HW, 1000 in-lb/in., AG	3	4(f)
$[45/0/-45/90]_{5s}$	Compression	HW, 1500 in-lb/in., AG	3	4(f)
$[45/0/-45/90]_{5s}$	Compression	RTD, 1500 in-lb/in., DW	1	4(f)

[a]RTD: room temperature, ambient moisture content; HW: 180°F, wet; DW: drop weight impact; AG: air gun impact.

Table 3. Tension Tests of 0° Laminates

(a) IM7/977-2

[Laminate, $[0]_8$; nominal thickness, 0.047 in.; nominal fiber volume fraction, 63.9 percent]

Specimen	Failure stress, ksi	Failure strain, percent	Modulus, Msi (*a*)	Poisson's ratio (*a*)
0T1	369.2	1.61	20.7	0.32
0T2	363.0	1.59	20.6	0.31
0T3	372.9	1.63	20.7	0.31
0T4	380.5	1.63	20.8	0.32
0T5	353.7	1.56	20.3	0.33
Average	367.9	1.60	20.6	0.32
Standard deviation	9.1	0.03	0.2	0.01

[a]Modulus and Poisson's ratio taken at 0.2 percent strain.

(b) IM7/F655

[Laminate, $[0]_8$; nominal thickness, 0.046 in.; nominal fiber volume fraction, 60.5 percent]

Specimen	Failure stress, ksi	Failure strain, percent	Modulus, Msi (*a*)	Poisson's ratio (*a*)
HEX0T1	367.2	1.54	21.8	0.32
HEX0T2	364.3	1.55	21.2	0.32
HEX0T3	375.2	1.59	21.6	0.33
HEX0T4	360.6	1.53	21.6	0.31
HEX0T5	358.6	1.58	20.8	0.32
Average	365.2	1.56	21.4	0.32
Standard deviation	5.8	0.02	0.4	0.01

[a]Modulus and Poisson's ratio taken at 0.2 percent strain.

Table 3. Concluded

(c) T800/F3900

[Laminate, $[0]_8$; nominal thickness, 0.044 in.; nominal fiber volume fraction, 64.9 percent]

Specimen	Failure stress, ksi	Failure strain, percent	Modulus, Msi (a)	Poisson's ratio (a)
TOR0T1	357.8	1.41	22.6	0.33
TOR0T2	358.4	1.48	22.1	0.32
TOR0T3	348.1	1.05	21.9	0.34
TOR0T4	361.6	1.51	21.4	0.33
TOR0T5	324.9	1.37	21.5	0.32
Average	350.2	1.36	21.9	0.33
Standard deviation	13.4	0.16	0.43	0.01

[a]Modulus and Poisson's ratio taken at 0.2 percent strain.

Table 4. Compression Tests of 0° Laminates

(a) IM7/977-2

[Laminate, $[0]_{16}$; nominal thickness, 0.091 in.; nominal fiber volume fraction, 61.4 percent]

Specimen	Failure[a] stress, ksi	Failure strain, percent	Modulus, Msi (*b*)	Poisson's ratio (*b*)
C6	131.8	0.70	19.8	0.28
C7	132.4	0.70	20.2	0.29
C8	130.9	0.68	21.1	0.28
Average	131.7	0.69	20.4	0.28
Standard deviation	0.6	0.01	0.5	0.01

[a]All specimens failed in "longitudinal splitting" mode.
[b]Modulus and Poisson's ratio taken at 0.2 percent strain.

(b) IM7/F655

[Laminate, $[0]_{16}$; nominal thickness, 0.092 in.; nominal fiber volume fraction, 58.8 percent]

Specimen	Failure[a] stress, ksi	Failure strain, percent	Modulus, Msi (*b*)	Poisson's ratio (*b*)
HEX0C1	145.8	0.73	21.2	0.31
HEX0C2	154.0	0.79	20.9	0.29
HEX0C3	159.2	0.83	20.8	0.29
HEX0C4	160.4	0.81	21.6	0.31
HEX0C5	160.6	0.82	21.3	0.30
Average	156.0	0.80	21.2	0.30
Standard deviation	5.6	0.04	0.3	0.01

[a]All specimens failed in "longitudinal splitting" mode.
[b]Modulus and Poisson's ratio taken at 0.2 percent strain.

Table 4. Concluded

(c) T800/F3900

[Laminate, $[0]_{24}$; nominal thickness, 0.133 in.; nominal fiber volume fraction, 60.3 percent]

Specimen	Failure[a] stress, ksi	Failure strain, percent	Modulus, Msi (b)	Poisson's ratio (b)
TOR0C1	137.3	0.66	21.7	0.37
TOR0C2	136.3	0.68	21.4	0.32
TOR0C3	133.3	0.67	21.0	0.31
TOR0C4	134.8	0.69	20.8	0.33
TOR0C5	123.7	0.62	20.5	0.32
Average	133.1	0.66	21.1	0.33
Standard deviation	4.9	0.02	0.4	0.02

[a]All specimens failed in "longitudinal splitting" mode.
[b]Modulus and Poisson's ratio taken at 0.2 percent strain.

Table 5. Tension Tests of 90° Laminates

(a) IM7/977-2

[Laminate, $[90]_8$; nominal thickness, 0.046 in.; nominal fiber volume fraction, 63.9 percent]

Specimen	Failure stress, ksi	Failure strain, percent	Modulus, Msi (a)	Poisson's ratio (a)
9T1	10.3	0.90	1.26	0.011
9T2	9.8	0.87	1.29	0.007
9T3	11.5	0.98	1.31	0.010
9T4	10.8	0.89	1.41	0.006
9T5	9.7	0.75	1.37	0.010
Average	10.4	0.88	1.33	0.009
Standard deviation	0.7	0.07	0.06	0.002

[a]Modulus and Poisson's ratio taken at 0.2 percent strain.

(b) IM7/F655

[Laminate, $[90]_8$; nominal thickness, 0.044 in.; nominal fiber volume fraction, 60.5 percent]

Specimen	Failure stress, ksi	Failure strain, percent	Modulus, Msi (a)	Poisson's ratio (a)
HEX9T1	6.6	0.48	1.51	0.012
HEX9T2	4.9	0.36	1.29	0.020
HEX9T3	5.4	0.44	1.29	0.014
HEX9T4	5.6	0.43	1.29	0.008
HEX9T5	4.8	0.35	1.34	0.007
Average	5.5	0.41	1.34	0.012
Standard deviation	0.7	0.05	0.09	0.005

[a]Modulus and Poisson's ratio taken at 0.2 percent strain.

Table 5. Concluded

(c) T800/F3900

[Laminate, $[90]_8$; nominal thickness, 0.045 in.; nominal fiber volume fraction, 64.9 percent]

Specimen	Failure stress, ksi	Failure strain, percent	Modulus, Msi (a)	Poisson's ratio (a)
TOR9T1	10.9	0.92	1.35	0.012
TOR9T2	10.5	0.91	1.37	0.011
TOR9T3	10.2	0.90	1.31	0.008
TOR9T4	9.8	0.87	1.26	0.015
TOR9T5	9.4	0.79	1.25	0.007
Average	10.2	0.88	1.31	0.011
Standard deviation	0.5	0.05	0.05	0.003

[a]Modulus and Poisson's ratio taken at 0.2 percent strain.

Table 6. Tension Tests of ±45° Laminates

(a) IM7/977-2

[Laminate, $[45/-45]_{2s}$; nominal thickness, 0.045 in.; nominal fiber volume fraction, 57.8 percent]

Specimen	Failure stress, ksi	Extensional modulus, Msi (a)	Shear modulus, ksi (b)	Poisson's ratio (b)
ST1	40.6	2.33	656	0.78
ST2	42.5	2.46	689	0.79
ST3	40.7	2.42	681	0.77
ST4	40.0	2.48	698	0.78
ST5	40.2	2.62	748	0.75
Average	40.8	2.46	694	0.77
Standard deviation	0.9	0.09	30	0.01

[a]Modulus and Poisson's ratio taken at 0.2 percent strain.
[b]In-plane shear modulus calculated for a 0° laminate.

(b) IM7/F655

[Laminate, $[45/-45]_{2s}$; nominal thickness, 0.047 in.; nominal fiber volume fraction, 57.5 percent]

Specimen	Failure stress, ksi	Extensional modulus, Msi (a)	Shear modulus, ksi (b)	Poisson's ratio (b)
HEXST1	31.0	2.72	787	0.73
HEXST2	33.6	2.86	827	0.73
HEXST3	32.3	2.75	800	0.72
HEXST4	29.8	2.83	831	0.70
HEXST5	28.0	2.74	800	0.71
Average	30.9	2.78	809	0.72
Standard deviation	1.9	0.06	17	0.01

[a]Modulus and Poisson's ratio taken at 0.2 percent strain.
[b]In-plane shear modulus calculated for a 0° laminate.

Table 6. Concluded

(c) T800/F3900

[Laminate, $[45/-45]_{2s}$; nominal thickness, 0.044 in.; nominal fiber volume fraction, 63.7 percent]

Specimen	Failure stress, ksi	Extensional modulus, Msi (*a*)	Shear modulus, ksi (*b*)	Poisson's ratio (*b*)
TORST1	39.5	2.63	743	0.77
TORST2	38.8	2.55	727	0.76
TORST3	39.4	2.54	723	0.76
TORST4	38.1	2.61	746	0.75
TORST5	37.7	2.64	759	0.75
Average	38.7	2.59	740	0.76
Standard deviation	0.7	0.04	13	0.01

[a]Modulus and Poisson's ratio taken at 0.2 percent strain.
[b]In-plane shear modulus calculated for a 0° laminate.

Table 7. Tension Tests of Quasi-Isotropic Unnotched Laminates

(a) IM7/977-2

[Laminate, $[45/0/-45/90]_{2s}$; nominal thickness, 0.092 in.; nominal fiber volume fraction, 57.3 percent]

Specimen	Failure stress, ksi	Failure strain, percent	Modulus, Msi (a)	Poisson's ratio (a)
QT1	145.3	1.32	8.21	0.30
QT2	136.1	1.70	7.78	0.30
QT3	130.6	1.64	7.75	0.30
QT4	132.7	1.67	7.68	0.30
QT5	136.1	1.70	7.74	0.29
Average	136.2	1.61	7.83	0.30
Standard deviation	5.0	0.14	0.19	0.004

[a]Modulus and Poisson's ratio taken at 0.2 percent strain.

(b) IM7/F655

[Laminate, $[45/0/-45/90]_{2s}$; nominal thickness, 0.092 in.; nominal fiber volume fraction, 61.6 percent]

Specimen	Failure stress, ksi	Failure strain, percent	Modulus, Msi (a)	Poisson's ratio (a)
HEXQT1	136.2	1.64	8.08	0.27
HEXQT2	124.0	1.51	8.06	0.28
HEXQT3	130.3	1.59	7.94	0.29
HEXQT4	130.6	1.57	8.16	0.28
HEXQT5	135.0	1.64	8.09	0.28
Average	131.2	1.59	8.07	0.28
Standard deviation	4.3	0.05	0.07	0.01

[a]Modulus and Poisson's ratio taken at 0.2 percent strain.

Table 7. Concluded

(c) T800/F3900

[Laminate, $[45/0/-45/90]_{2s}$; nominal thickness, 0.089 in.; nominal fiber volume fraction, 59.7 percent]

Specimen	Failure stress, ksi	Failure strain, percent	Modulus, Msi (*a*)	Poisson's ratio (*a*)
TORQT1	131.8	1.58	8.20	0.29
TORQT2	146.1	1.73	8.14	0.29
TORQT3	149.9	1.76	8.30	0.29
TORQT4	147.8	1.76	8.20	0.29
TORQT5	144.8	1.76	8.09	0.31
Average	144.1	1.72	8.19	0.29
Standard deviation	6.4	0.07	0.07	0.01

[a]Modulus and Poisson's ratio taken at 0.2 percent strain.

Table 8. Tension Tests of Quasi-Isotropic Notched Laminates

(a) IM7/977-2

[Laminate, $[45/0/-45/90]_{2S}$; nominal thickness, 0.092 in.; nominal fiber volume fraction, 57.3 percent]

Specimen	Width, in.	Hole diam., in.	Failure stress, ksi (a)	Failure strain, percent (b)
HT1	3.00	0.50	60.1	0.727
HT2	3.00	0.50	56.9	0.704
HT3	3.00	0.50	56.9	0.684
Average			58.0	0.705
Standard deviation			1.5	0.018
HT4	1.50	0.25	63.5	0.820
HT5	1.50	0.25	61.3	0.789
HT6	1.50	0.25	67.2	0.860
Average			64.0	0.823
Standard deviation			2.4	0.029

[a]Maximum stress based on gross specimen cross-sectional area.
[b]Failure strain measured by gauges.

(b) IM7/F655

[Laminate, $[45/0/-45/90]_{2S}$; nominal thickness, 0.092 in.; nominal fiber volume fraction, 61.1 percent]

Specimen	Width, in.	Hole diam., in.	Failure stress, ksi (a)	Failure strain, percent (b)
HEXHT1	3.00	0.50	58.2	0.486
HEXHT2	3.00	0.50	56.3	0.487
HEXHT3	3.00	0.50	62.4	0.534
Average			59.0	0.502
Standard deviation			2.5	0.022
HEXHT4	1.50	0.25	71.5	0.628
HEXHT5	1.50	0.25	72.6	0.634
HEXHT6	1.50	0.25	68.6	0.626
Average			70.9	0.629
Standard deviation			1.7	0.003

[a]Maximum stress based on gross specimen cross-sectional area.
[b]Failure strain measured by gauges.

Table 8. Concluded

(c) T800/F3900

[Laminate, $[45/0/-45/90]_{2s}$; nominal thickness, 0.089 in.; nominal fiber volume fraction, 59.7 percent]

Specimen	Width, in.	Hole diam., in	Failure stress, ksi (*a*)	Failure strain, percent (*b*)
TORHT1	3.00	0.50	58.3	0.686
TORHT2	3.00	0.50	58.2	0.691
TORHT3	3.00	0.50	58.1	0.698
Average			58.2	0.692
Standard deviation			0.1	0.005
TORHT4	1.50	0.25	68.2	0.837
TORHT5	1.50	0.25	67.0	0.813
TORHT6	1.50	0.25	66.6	0.811
Average			67.3	0.820
Standard deviation			0.7	0.012

[a]Maximum stress based on gross specimen cross-sectional area.
[b]Failure strain measured by gauges.

Table 9. Compression Tests of Quasi-Isotropic Unnotched Laminates

(a) IM7/977-2

[Laminate, $[45/0/-45/90]_{5s}$; nominal thickness, 0.229 in.; nominal fiber volume fraction, 56.7 percent]

Specimen	Failure stress, ksi	Failure strain, percent	Modulus, Msi (a)	Poisson's ratio (a)
C1	96.1	1.54	6.92	0.30
C2	101.9	1.64	7.05	0.30
C3	92.4	1.44	7.08	0.29
C4	93.0	1.46	7.03	0.31
C5	89.3	1.39	7.07	0.30
Average	94.5	1.49	7.03	0.30
Standard deviation	4.3	0.09	0.06	0.004

[a]Modulus and Poisson's ratio taken at 0.2 percent strain.

(b) IM7/F655

[Laminate, $[45/0/-45/90]_{5s}$; nominal thickness, 0.225 in.; nominal fiber volume fraction, 59.1 percent]

Specimen	Failure stress, ksi	Failure strain, percent	Modulus, Msi (a)	Poisson's ratio (a)
HEXC1	106.3	1.64	7.92	0.29
HEXC2	97.1	1.55	7.23	0.30
HEXC3	104.0	1.60	7.42	0.29
HEXC4	95.7	1.46	7.22	0.28
HEXC5	98.0	1.52	7.09	0.28
Average	100.2	1.55	7.38	0.29
Standard deviation	4.2	0.06	0.29	0.01

[a]Modulus and Poisson's ratio taken at 0.2 percent strain.

Table 9. Concluded

(c) T800/F3900

[Laminate, $[45/0/-45/90]_{5s}$; nominal thickness, 0.231 in.; nominal fiber volume fraction, 55.6 percent]

Specimen	Failure stress, ksi	Failure strain, percent	Modulus, Msi (a)	Poisson's ratio (a)
TORC1	89.8	1.36	7.69	0.31
TORC2	91.2	1.44	7.44	0.31
TORC3	89.9	1.40	7.45	0.32
TORC4	93.1	1.48	7.40	0.30
TORC5	92.5	1.51	7.31	0.31
Average	91.3	1.44	7.46	0.31
Standard deviation	1.3	0.05	0.13	0.01

[a]Modulus and Poisson's ratio taken at 0.2 percent strain.

Table 10. Compression Tests of Quasi-Isotropic Notched Laminates

(a) IM7/977-2

[Laminate, $[45/0/-45/90]_{5s}$; nominal thickness, 0.230 in.; nominal fiber volume fraction, 57.1 percent]

Specimen	Width, in.	Hole diam., in.	Failure stress, ksi (a)	Failure strain, percent (b)	Condition (c)
HC1	5.00	1.00	37.4	0.499	RTD
HC2	5.00	1.00	36.1	0.482	RTD
HC3	5.00	1.00	38.4	0.514	RTD
Average			37.3	0.498	
Standard deviation			0.9	0.013	
HC4	3.00	0.25	51.7	0.695	RTD
HC5	3.00	0.25	51.7	0.699	RTD
HC6	3.00	0.25	50.7	0.683	RTD
Average			51.4	0.692	
Standard deviation			0.5	0.007	
HC7	3.00	0.50	41.3	0.528	RTD
HC8	3.00	0.50	40.3	0.527	RTD
HC9	3.00	0.50	39.9	0.511	RTD
Average			40.5	0.522	
Standard deviation			0.6	0.008	
HC10	3.00	0.25	39.6	0.543	HW
HC11	3.00	0.25	40.1	0.561	HW
HC12	3.00	0.25	39.7	0.552	HW
Average			39.8	0.552	
Standard deviation			0.2	0.007	

[a]Maximum stress based on gross specimen cross-sectional area.
[b]Failure strain measured by gauges.
[c]RTD: Room temperature, ambient moisture content; HW: 180°F, wet.

Table 10. Continued

(b) IM7/F655

[Laminate, $[45/0/-45/90]_{5s}$; nominal thickness, 0.225 in.; nominal fiber volume fraction, 59.6 percent]

Specimen	Width, in.	Hole diam., in.	Failure stress, ksi (*a*)	Failure strain, percent (*b*)	Condition (*c*)
HEXHC1	5.00	1.00	39.1	0.488	RTD
HEXHC2	5.00	1.00	38.5	0.491	RTD
HEXHC3	5.00	1.00	40.4	0.516	RTD
Average			39.3	0.498	
Standard deviation			0.8	0.013	
HEXHC4	3.00	0.25	50.1	0.652	RTD
HEXHC5	3.00	0.25	52.9	0.694	RTD
HEXHC6	3.00	0.25	54.5	0.698	RTD
Average			52.5	0.681	
Standard deviation			1.8	0.021	
HEXHC7	3.00	0.50	44.7	0.557	RTD
HEXHC8	3.00	0.50	44.9	0.568	RTD
HEXHC9	3.00	0.50	46.2	0.578	RTD
Average			45.3	0.568	
Standard deviation			0.7	0.009	
HEXHC10	3.00	0.25	44.3	0.594	HW
HEXHC11	3.00	0.25	44.8	0.608	HW
HEXHC12	3.00	0.25	44.7	0.597	HW
Average			44.6	0.600	
Standard deviation			0.2	0.006	

[a]Maximum stress based on gross specimen cross-sectional area.
[b]Failure strain measured by gauges.
[c]RTD: Room temperature, ambient moisture content; HW: 180°F, wet.

Table 10. Concluded

(c) T800/F3900

[Laminate, $[45/0/-45/90]_{5s}$; nominal thickness, 0.231 in.; nominal fiber volume fraction, 56.6 percent]

Specimen	Width, in.	Hole diam., in.	Failure stress, ksi (*a*)	Failure strain, percent (*b*)	Condition (*c*)
TORHC1	5.00	1.00	36.9	0.480	RTD
TORHC2	5.00	1.00	35.4	0.463	RTD
TORHC3	5.00	1.00	38.0	0.495	RTD
Average			36.8	0.479	
Standard deviation			1.1	0.013	
TORHC4	3.00	0.25	51.5	0.703	RTD
TORHC5	3.00	0.25	50.1	0.719	RTD
TORHC6	3.00	0.25	51.7	0.716	RTD
Average			51.1	0.713	
Standard deviation			0.7	0.007	
TORHC7	3.00	0.50	41.9	0.541	RTD
TORHC8	3.00	0.50	40.0	0.538	RTD
TORHC9	3.00	0.50	42.5	0.552	RTD
Average			41.5	0.544	
Standard deviation			1.1	0.006	
TORHC10	3.00	0.25	39.1	0.550	HW
TORHC11	3.00	0.25	39.1	0.571	HW
TORHC12	3.00	0.25	39.4	0.551	HW
Average			39.2	0.557	
Standard deviation			0.1	0.010	

[a]Maximum stress based on gross specimen cross-sectional area.
[b]Failure strain measured by gauges.
[c]RTD: Room temperature, ambient moisture content; HW: 180°F, wet.

Table 11. Compression Tests of Post-Impact Laminates

(a) IM7/977-2

[Laminate, $[45/0/-45/90]_{5s}$; nominal thickness, 0.230 in.; nominal fiber volume fraction, 57.6 percent]

Specimen	Impact energy, in-lb/in.	Damage area, in^2	Failure stress, ksi	Failure strain, percent	Condition (a)
CAI1	1000 (19 ft-lb)	1.83	31.7	0.43	AG,RTD
CAI2	1000 (19 ft-lb)	1.85	31.6	0.43	AG,RTD
CAI3	1000 (19 ft-lb)	1.76	30.9	0.42	AG,RTD
Average		1.81	31.4	0.43	
Standard deviation		0.05	0.4	0.01	
CAI7	1000 (19 ft-lb)	1.80	31.1	0.43	AG,HW
CAI8	1000 (19 ft-lb)	1.75	29.5	0.41	AG,HW
CAI9	1000 (19 ft-lb)	1.91	28.3	0.38	AG,HW
Average		1.82	29.6	0.41	
Standard deviation		0.08	1.1	0.02	
CAI4	1500 (29 ft-lb)	3.45	25.0	0.34	AG,RTD
CAI5	1500 (29 ft-lb)	3.66	25.9	0.35	AG,RTD
CAI6	1500 (29 ft-lb)	3.68	25.4	0.25	AG,RTD
Average		3.60	25.4	0.31	
Standard deviation		0.12	0.4	0.04	
CAI10	1500 (29 ft-lb)	3.44	26.7	0.36	AG,HW
CAI11	1500 (29 ft-lb)	3.59	23.7	0.32	AG,HW
CAI12	1500 (29 ft-lb)	3.87	23.0	0.31	AG,HW
Average		3.63	24.5	0.33	
Standard deviation		0.22	1.6	0.02	
DI1	1500 (29 ft-lb)	2.61	39.2	0.53	DW,RTD

[a] AG: air gun impact; DW: drop weight impact; RTD: room temperature, ambient moisture content; HW: 180°F, wet.

Table 11. Continued

(b) IM7/F655

$\left[\begin{array}{c}\text{Laminate, } [45/0/-45/90]_{5s}\text{; nominal thickness, 0.224 in.;}\\ \text{nominal fiber volume fraction, 59.3 percent}\end{array}\right]$

Specimen	Impact energy, in-lb/in.	Damage area, in^2	Failure stress, ksi	Failure strain, percent	Condition (*a*)
HEXCAI1	1000 (19 ft-lb)	2.87	26.5	0.33	AG,RTD
HEXCAI2	1000 (19 ft-lb)	2.74	27.1	0.34	AG,RTD
HEXCAI3	1000 (19 ft-lb)	2.65	27.1	0.34	AG,RTD
Average		2.75	26.9	0.34	
Standard deviation		0.11	0.3	0.004	
HEXCAI8	1000 (19 ft-lb)	2.56	28.7	0.39	AG,HW
HEXCAI9	1000 (19 ft-lb)	2.88	26.6	0.35	AG,HW
HEXCAI10	1000 (19 ft-lb)	3.90	29.1	0.39	AG,HW
Average		3.11	28.1	0.38	
Standard deviation		0.70	1.1	0.02	
HEXCAI4	1500 (29 ft-lb)	4.16	23.1	0.29	AG,RTD
HEXCAI6	1500 (29 ft-lb)	4.19	24.0	0.30	AG,RTD
HEXCAI7	1500 (29 ft-lb)	4.63	24.2	0.30	AG,RTD
Average		4.33	23.8	0.30	
Standard deviation		0.26	0.5	0.01	
HEXCAI11	1500 (29 ft-lb)	4.70	21.9	0.29	AG,HW
HEXCAI12	1500 (29 ft-lb)	4.74	22.4	0.29	AG,HW
HEXCAI13	1500 (29 ft-lb)	4.96	21.6	0.27	AG,HW
Average		4.80	22.0	0.28	
Standard deviation		0.14	0.3	0.01	
HEXDI1	1500 (29 ft-lb)	4.28	32.3	0.41	DW,RTD

[a]AG: air gun impact; DW: drop weight impact; RTD: room temperature, ambient moisture content; HW: 180°F, wet.

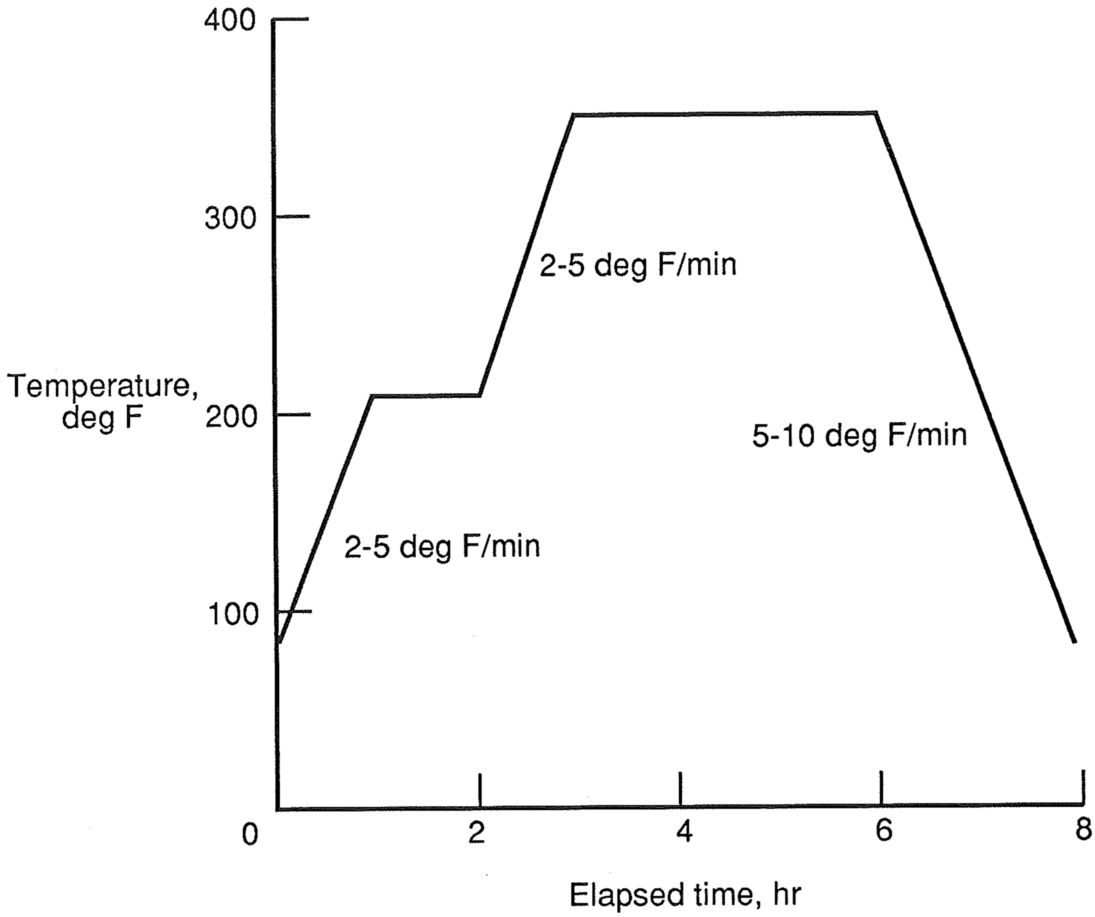
Table 11. Concluded

(c) T800/F3900

[Laminate, $[45/0/-45/90]_{5s}$; nominal thickness, 0.222 in.; nominal fiber volume fraction, 59.1 percent]

Specimen	Impact energy, in-lb/in.	Damage area, in^2	Failure stress, ksi	Failure strain, percent	Condition (*a*)
TORCAI1	1000 (19 ft-lb)	1.09	44.0	0.57	AG,RTD
TORCAI2	1000 (19 ft-lb)	0.72	43.6	0.57	AG,RTD
TORCAI3	1000 (19 ft-lb)	1.34	42.4	0.55	AG,RTD
Average		1.05	43.3	0.56	
Standard deviation		0.31	0.7	0.01	
TORCAI7	1000 (19 ft-lb)	1.16	36.6	0.49	AG,HW
TORCAI8	1000 (19 ft-lb)	1.09	34.4	0.46	AG,HW
TORCAI9	1000 (19 ft-lb)	1.06	37.4	0.51	AG,HW
Average		1.10	36.1	0.49	
Standard deviation		0.05	1.3	0.02	
TORCAI4	1500 (29 ft-lb)	2.09	35.0	0.45	AG,RTD
TORCAI5	1500 (29 ft-lb)	2.31	35.4	0.46	AG,RTD
TORCAI6	1500 (29 ft-lb)	2.22	36.3	0.46	AG,RTD
Average		2.21	35.6	0.46	
Standard deviation		0.11	0.5	0.01	
TORCAI10	1500 (29 ft-lb)	2.23	29.6	0.39	AG,HW
TORCAI11	1500 (29 ft-lb)	1.96	29.9	0.40	AG,HW
TORCAI12	1500 (29 ft-lb)	2.20	28.1	0.37	AG,HW
Average		2.13	29.2	0.39	
Standard deviation		0.14	0.8	0.01	
TORDI1	1500 (29 ft-lb)	1.72	39.9	0.51	DW,RTD

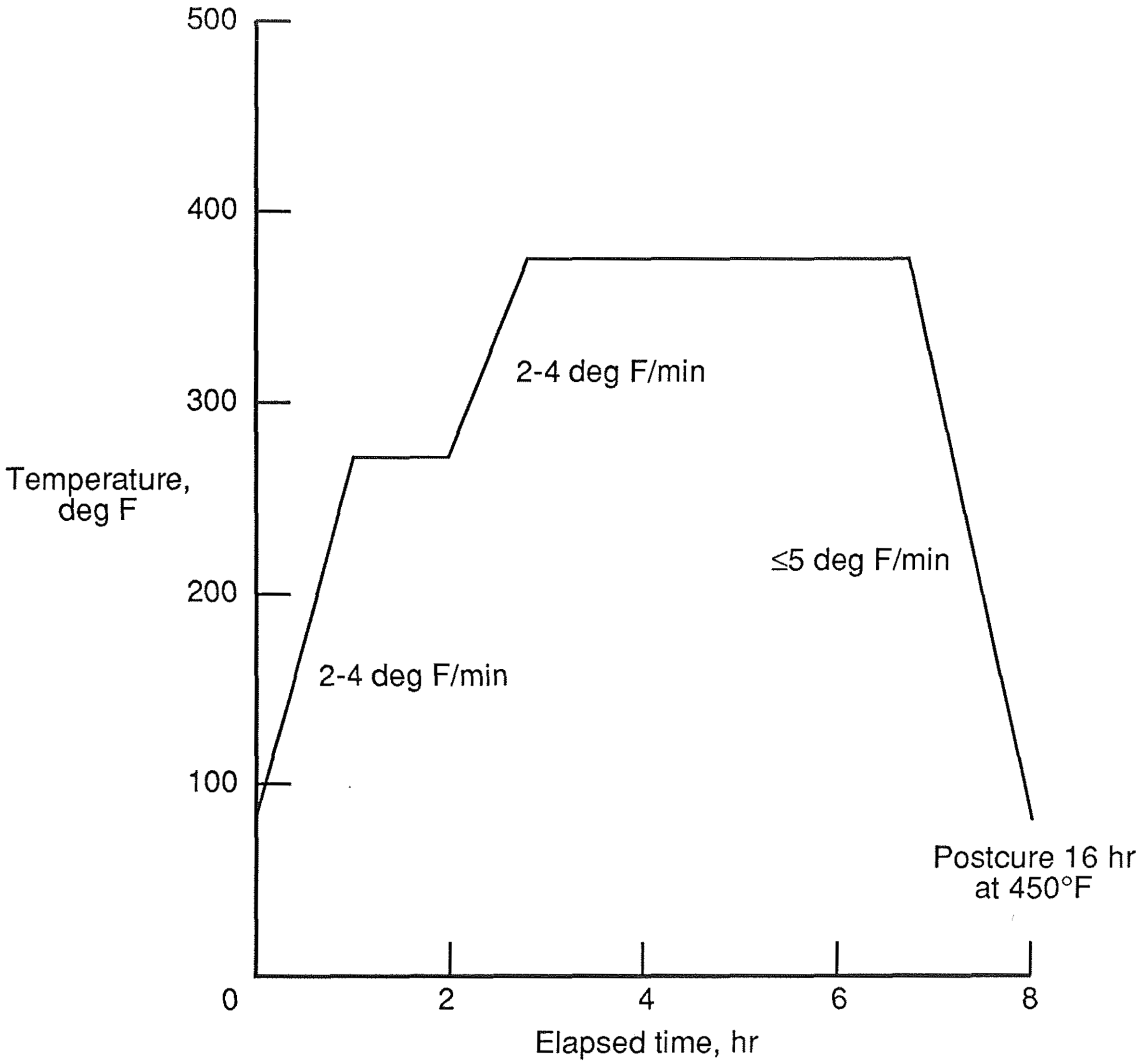
[a]AG: air gun impact; DW: drop weight impact; RTD: room temperature, ambient moisture content; HW: 180°F, wet.



Cure process:

1. Apply 22 in. Hg vacuum to bag
2. Apply 100 psig pressure to laminate when temperature reaches 200°F
3. Vent vacuum when pressure reaches 20 psig
4. Release pressure after cooling

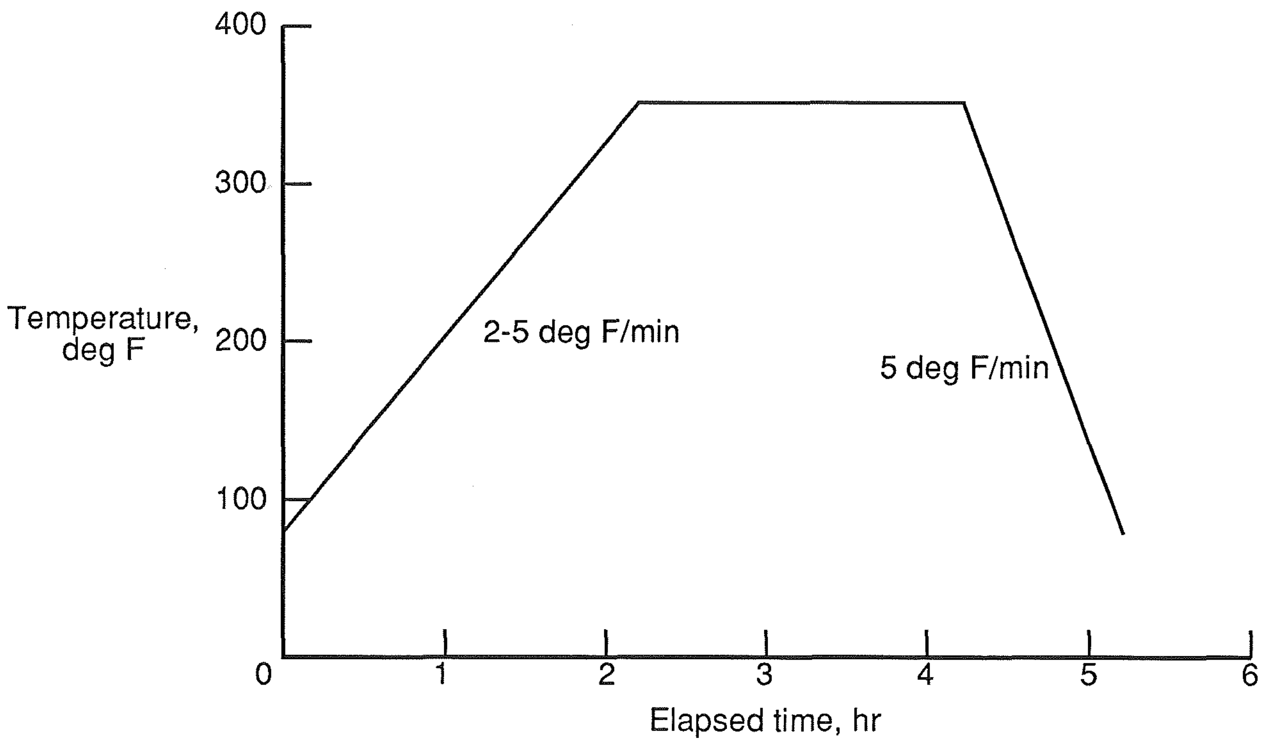
Figure 1. Manufacturer's recommended cure cycle for 977-2.



Cure process:

1. Apply 22 in. Hg vacuum to bag
2. Hold at 270°F for 30 min with vacuum only
3. Apply 85 psig pressure to laminate and dwell an additional 30 min
4. Release vacuum
5. Release pressure after cooling

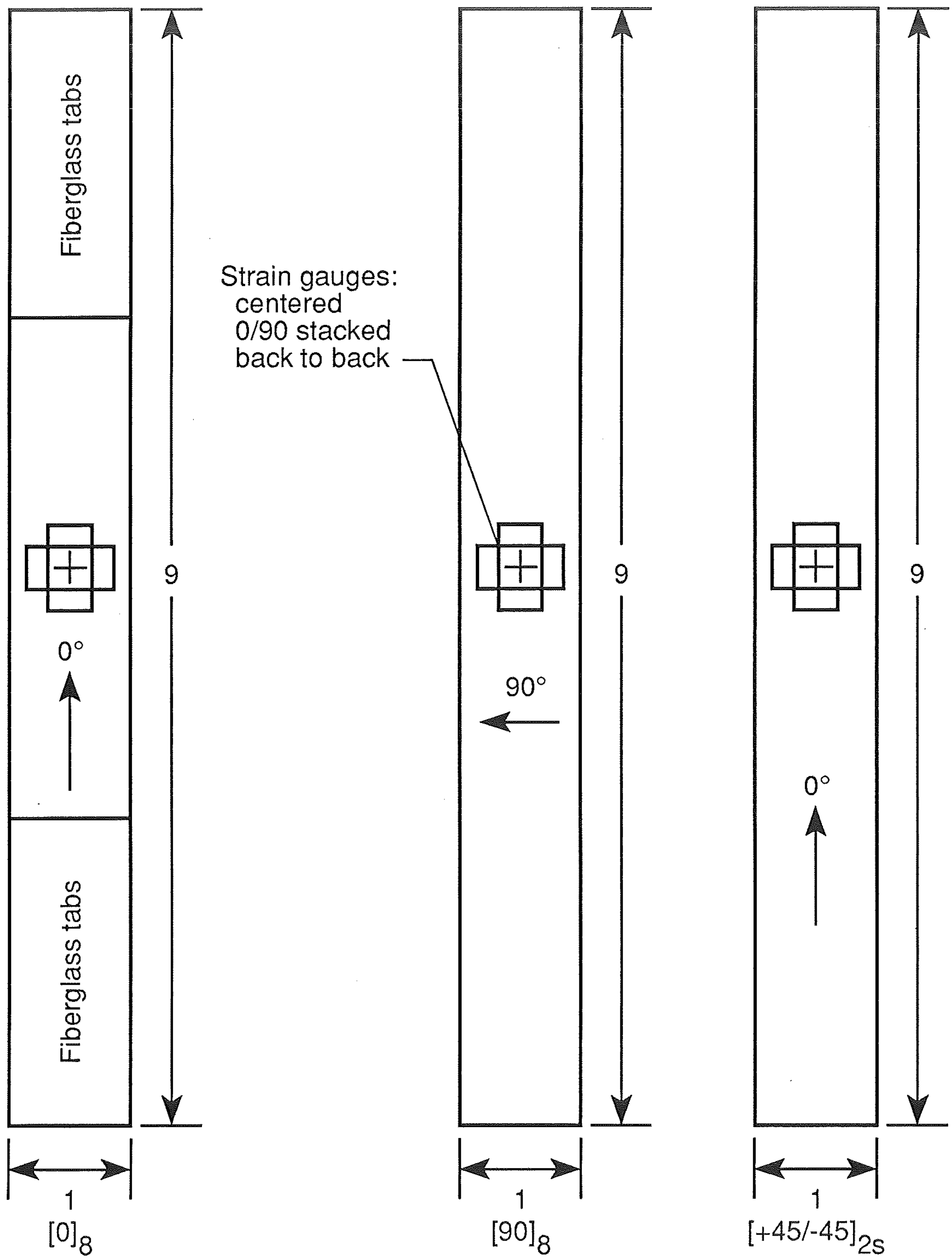
Figure 2. Manufacturer's recommended cure cycle for F655.



Cure process:

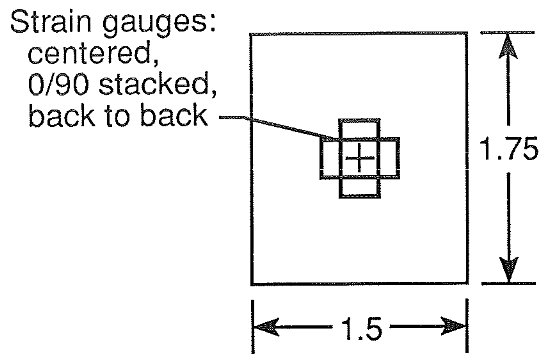
1. Apply 22 in. Hg vacuum to bag
2. Apply 85 psig pressure to laminate
3. Vent vacuum when pressure reaches 20 psig
4. Release pressure after cooling

Figure 3. Manufacturer's recommended cure cycle for F3900.

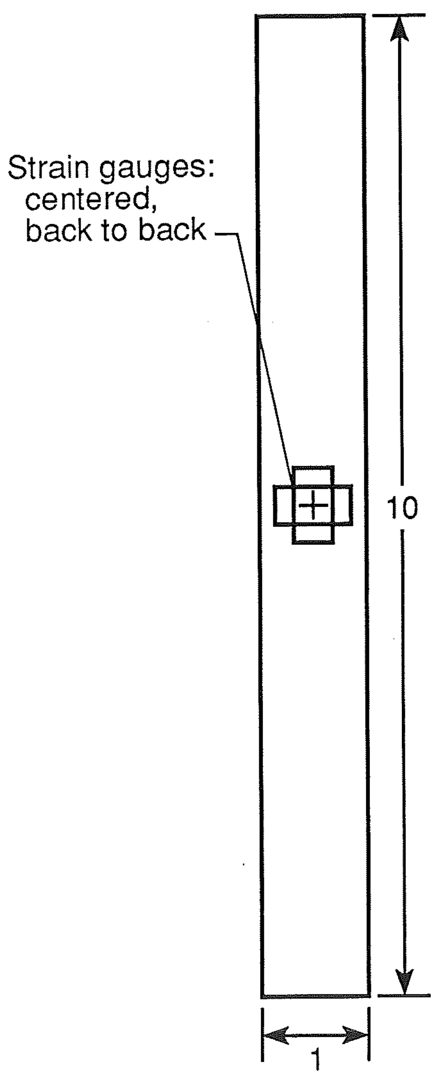


(a) Ply-level tension specimens.

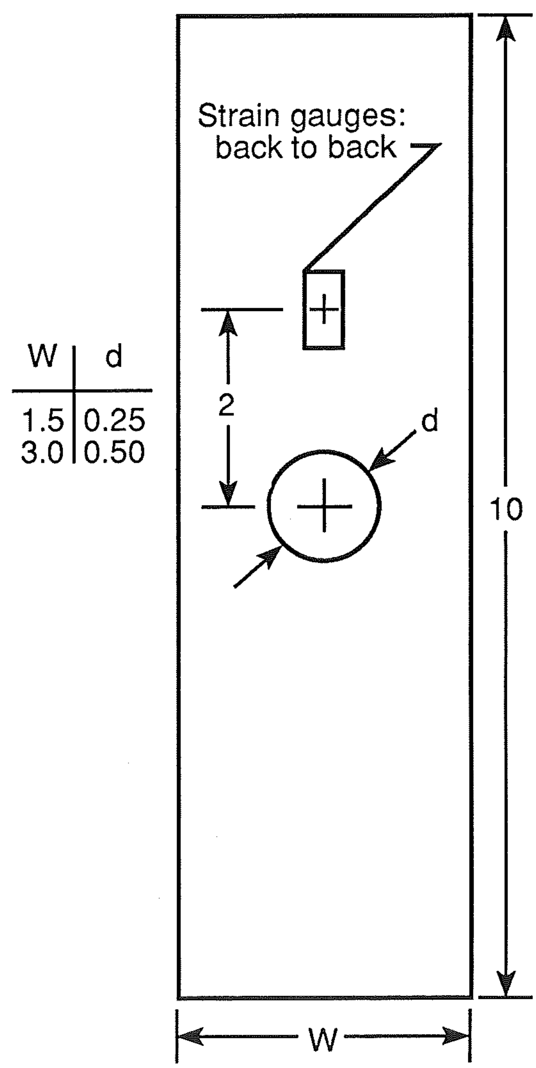
Figure 4. Test specimen configurations. All dimensions are in inches.



(b) Short-block compression specimen.

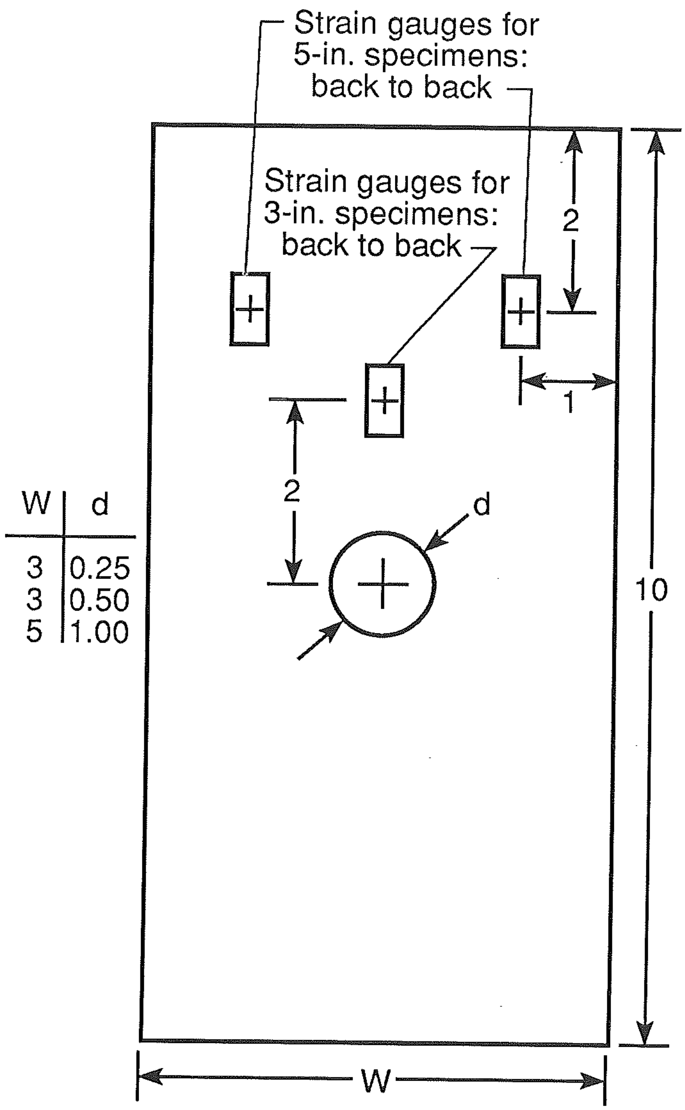


(c) Unnotched tension specimen for quasi-isotropic laminates.

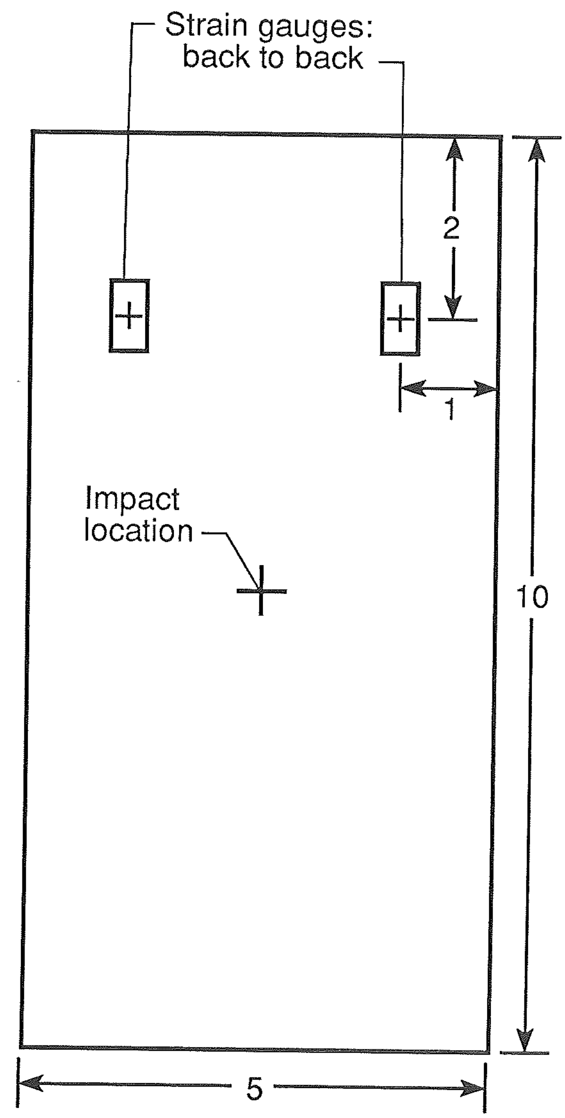


(d) Open-hole tension specimens.

Figure 4. Continued.

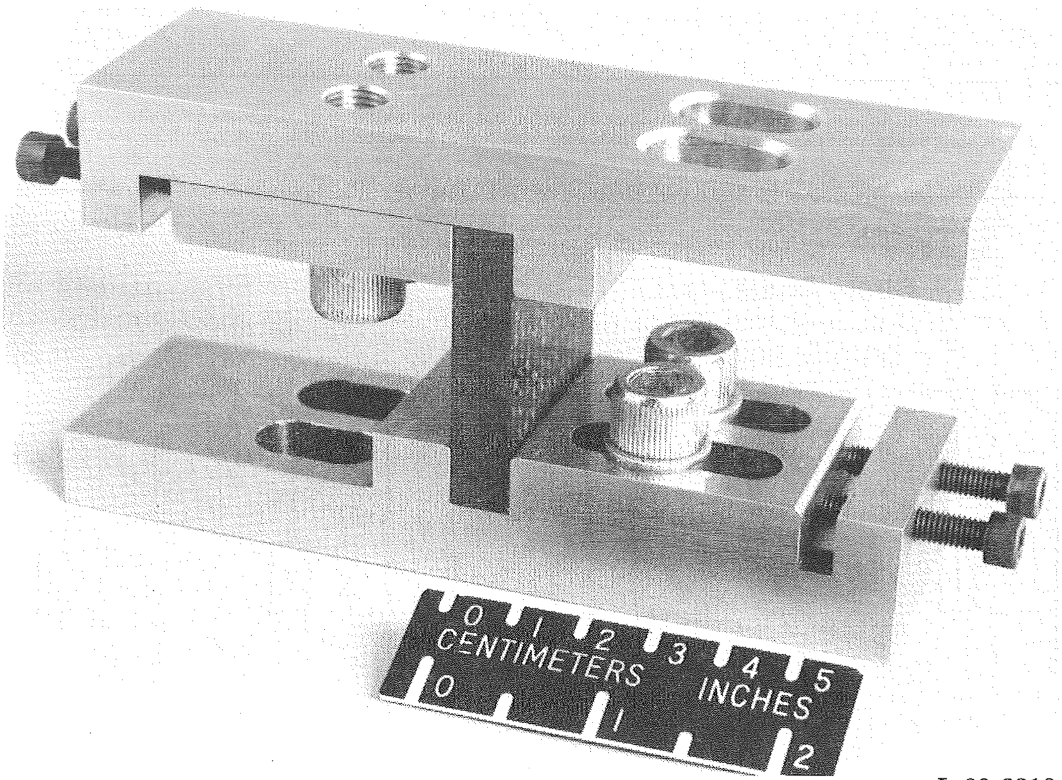


(e) Open-hole compression specimens.



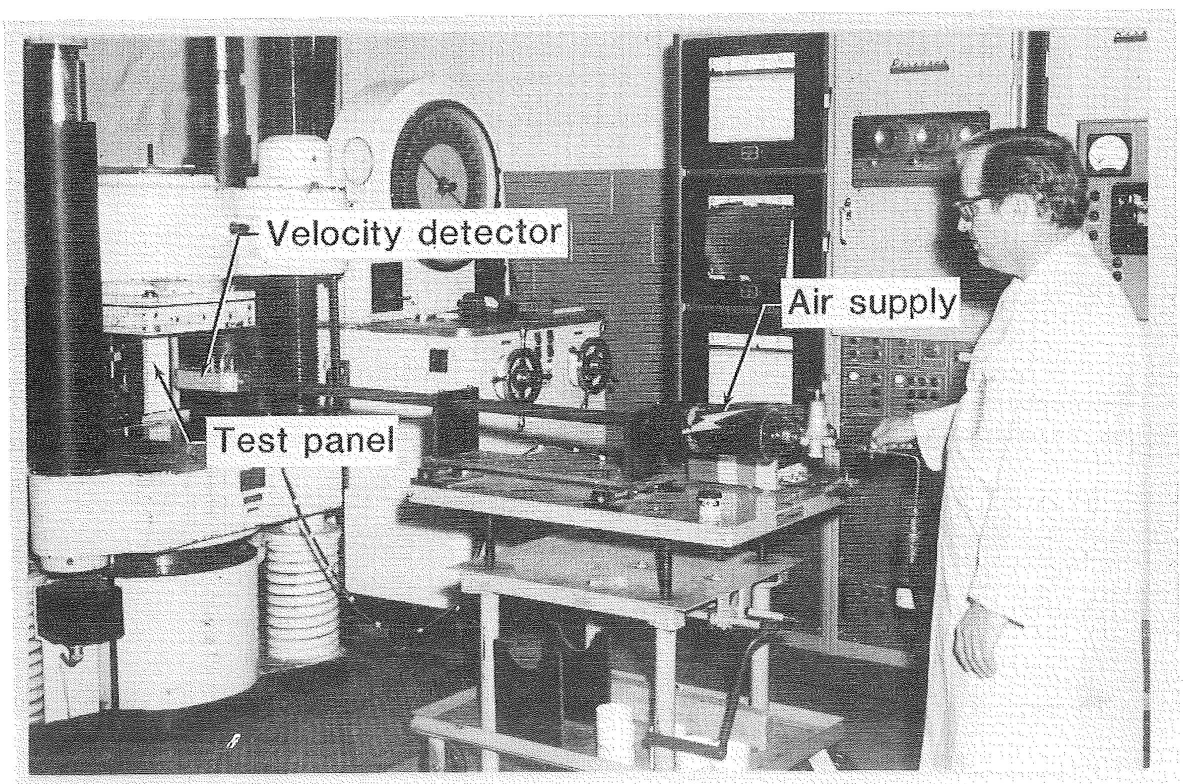
(f) Compression after impact specimen.

Figure 4. Concluded.



L-89-3310

Figure 5. Short-block compression fixture.



L-85-13448

Figure 6. Impact test apparatus.

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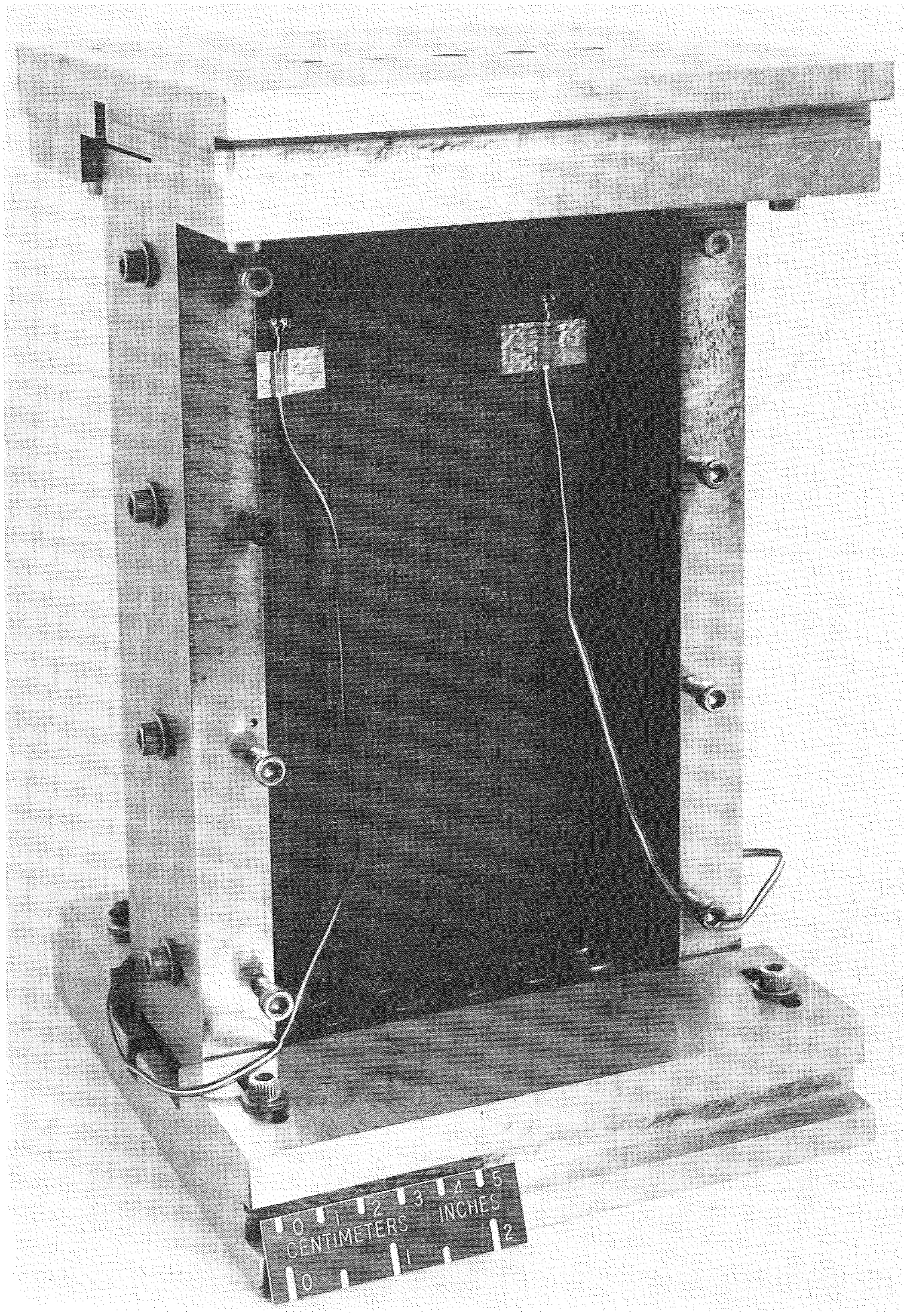


L-85-11872

Figure 7. Compression-after-impact test fixture.

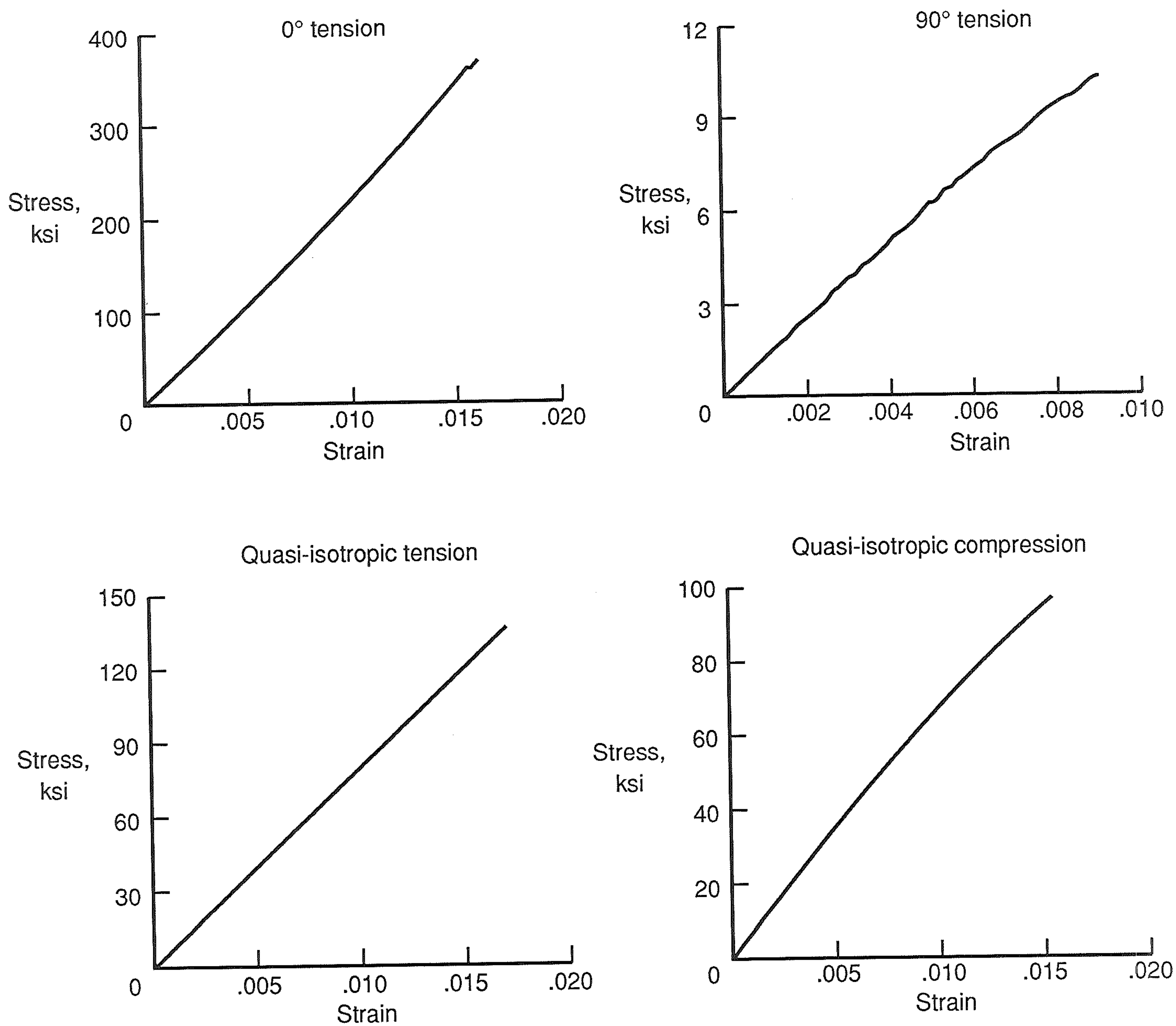


Figure 8. Typical stress-strain plots for IM7/977-2 laminates.

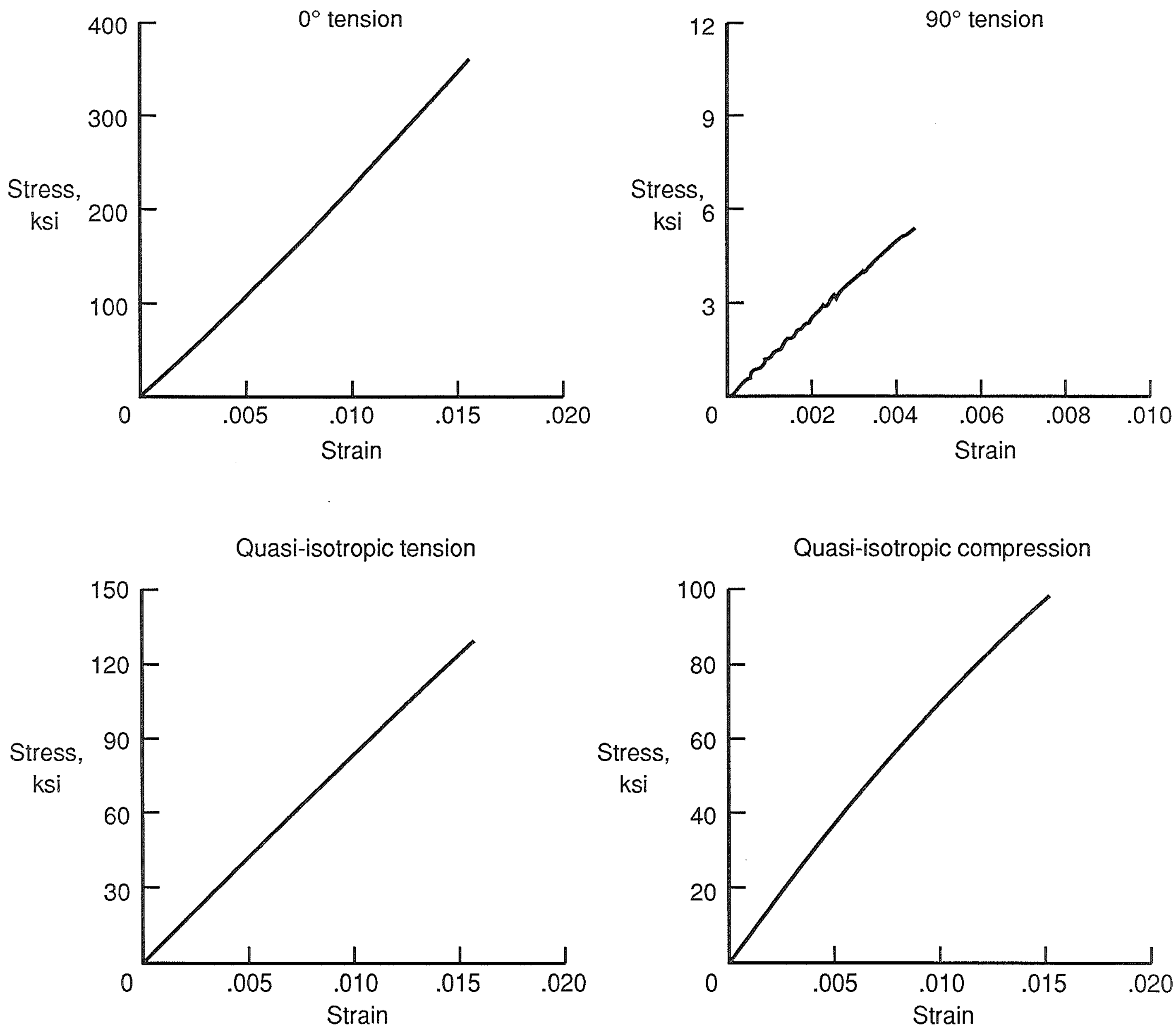


Figure 9. Typical stress-strain plots for IM7/F655 laminates.

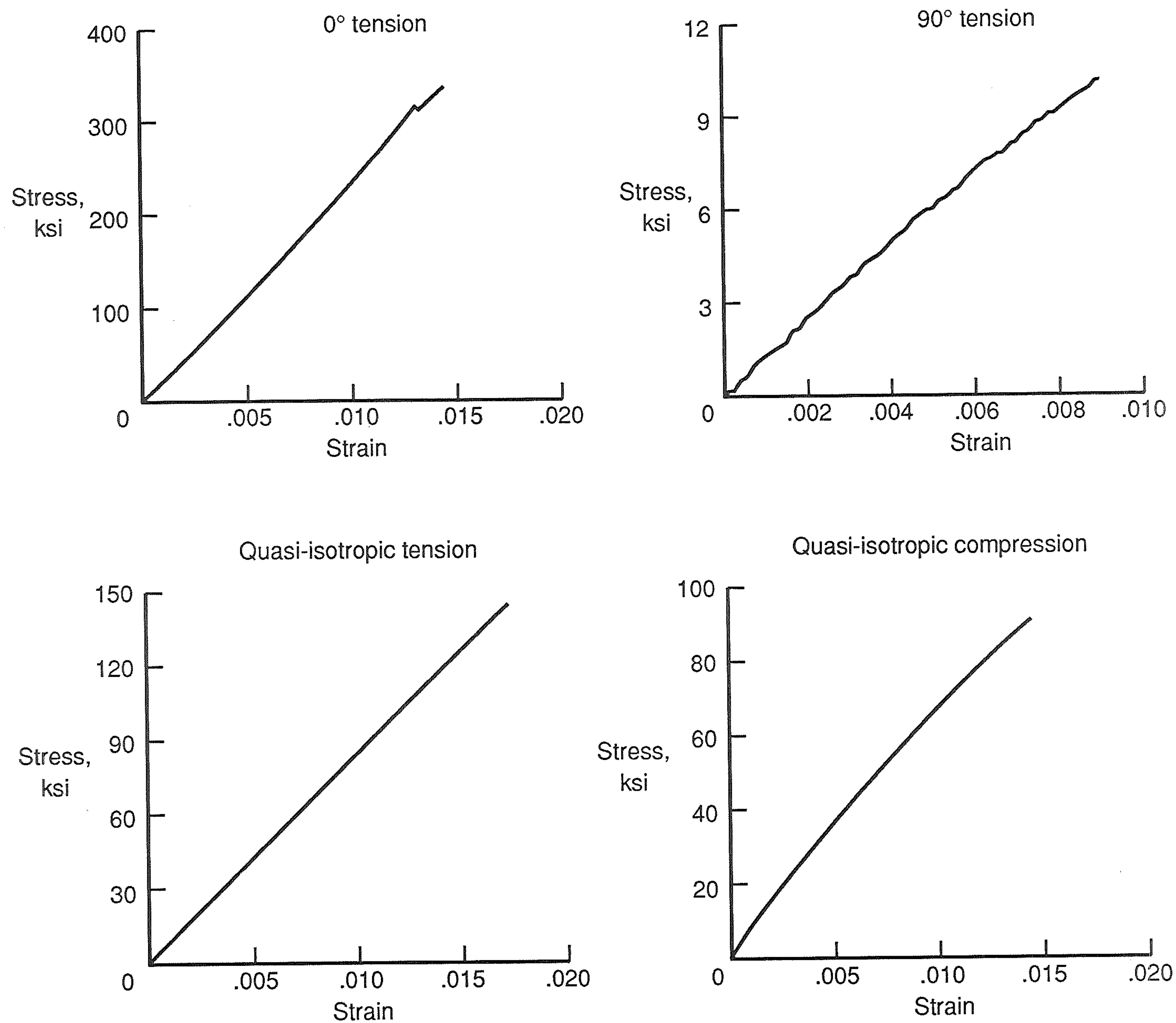


Figure 10. Typical stress-strain plots for T800/F3900 laminates.

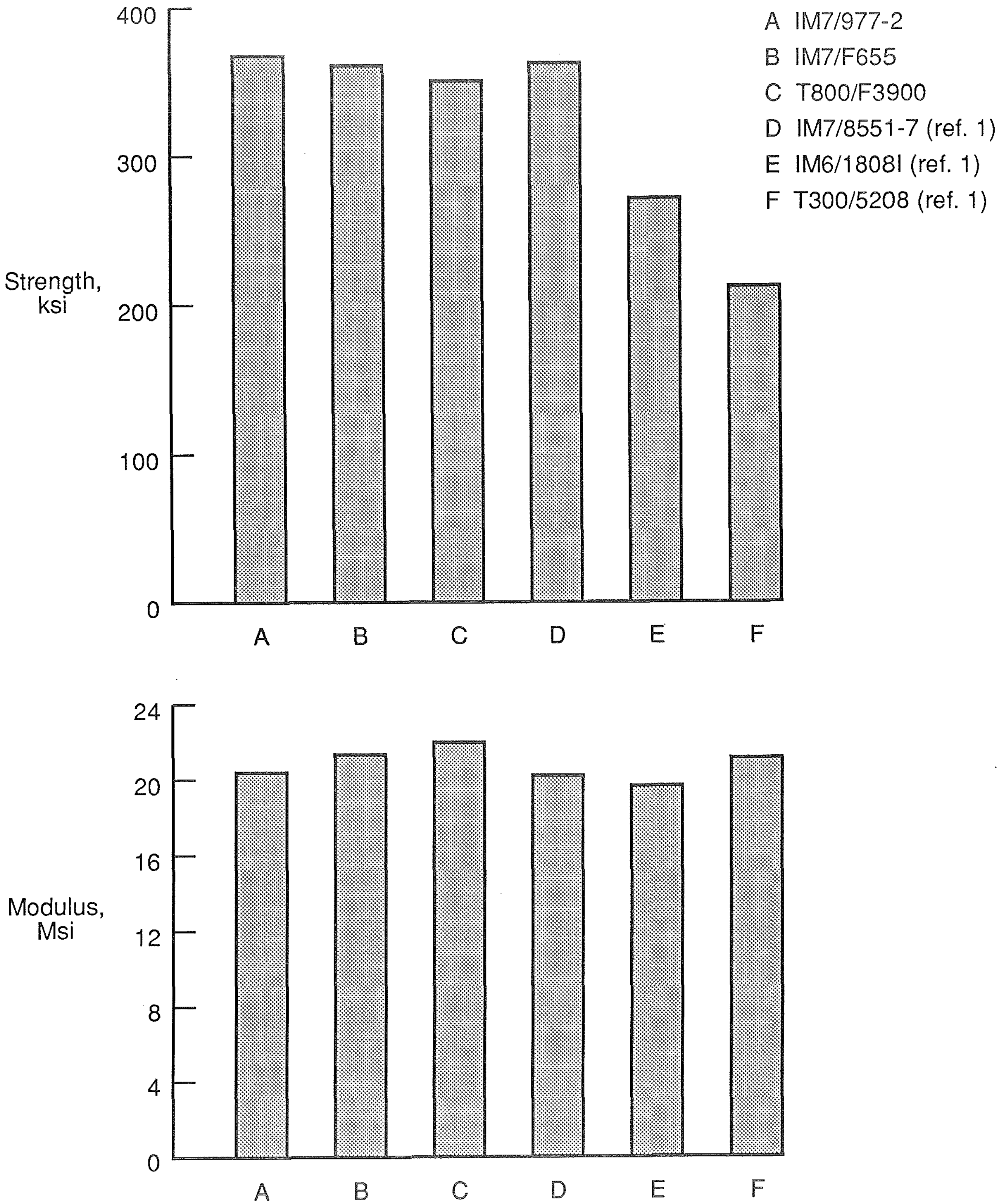


Figure 11. Tension strengths and moduli for 0° laminates.

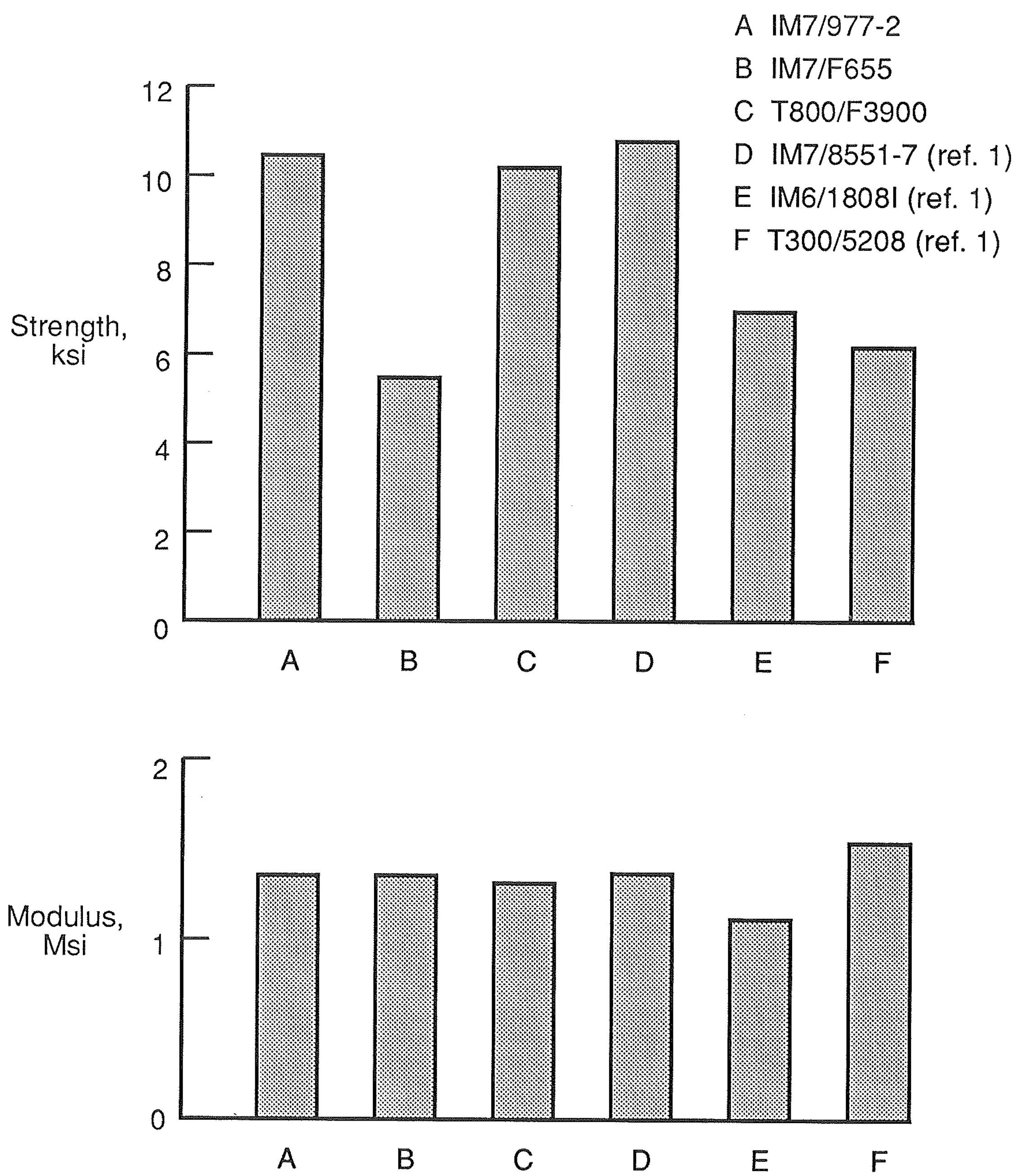


Figure 12. Tension strengths and moduli for 90° laminates.

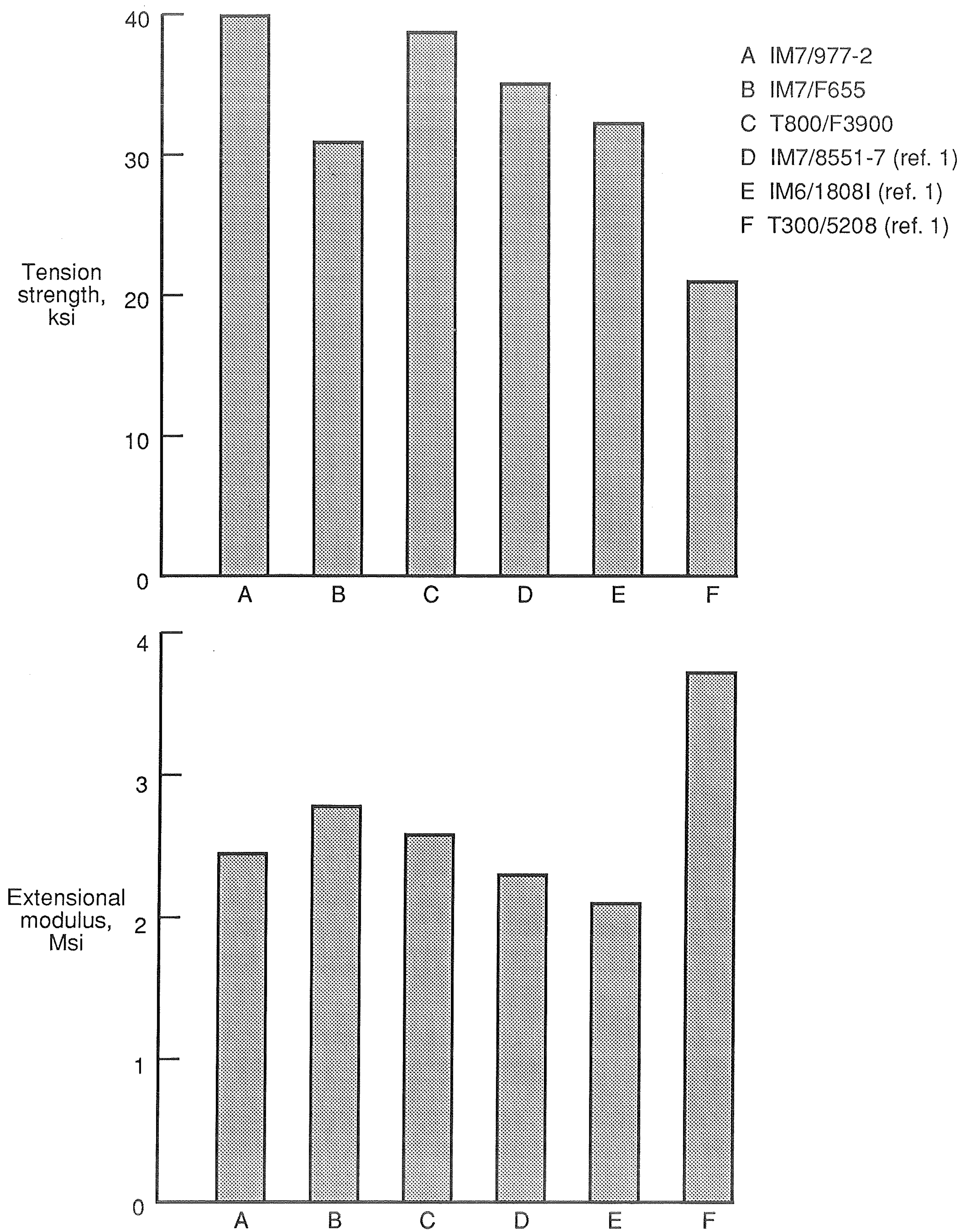


Figure 13. Tension strengths and moduli for ±45° laminates.

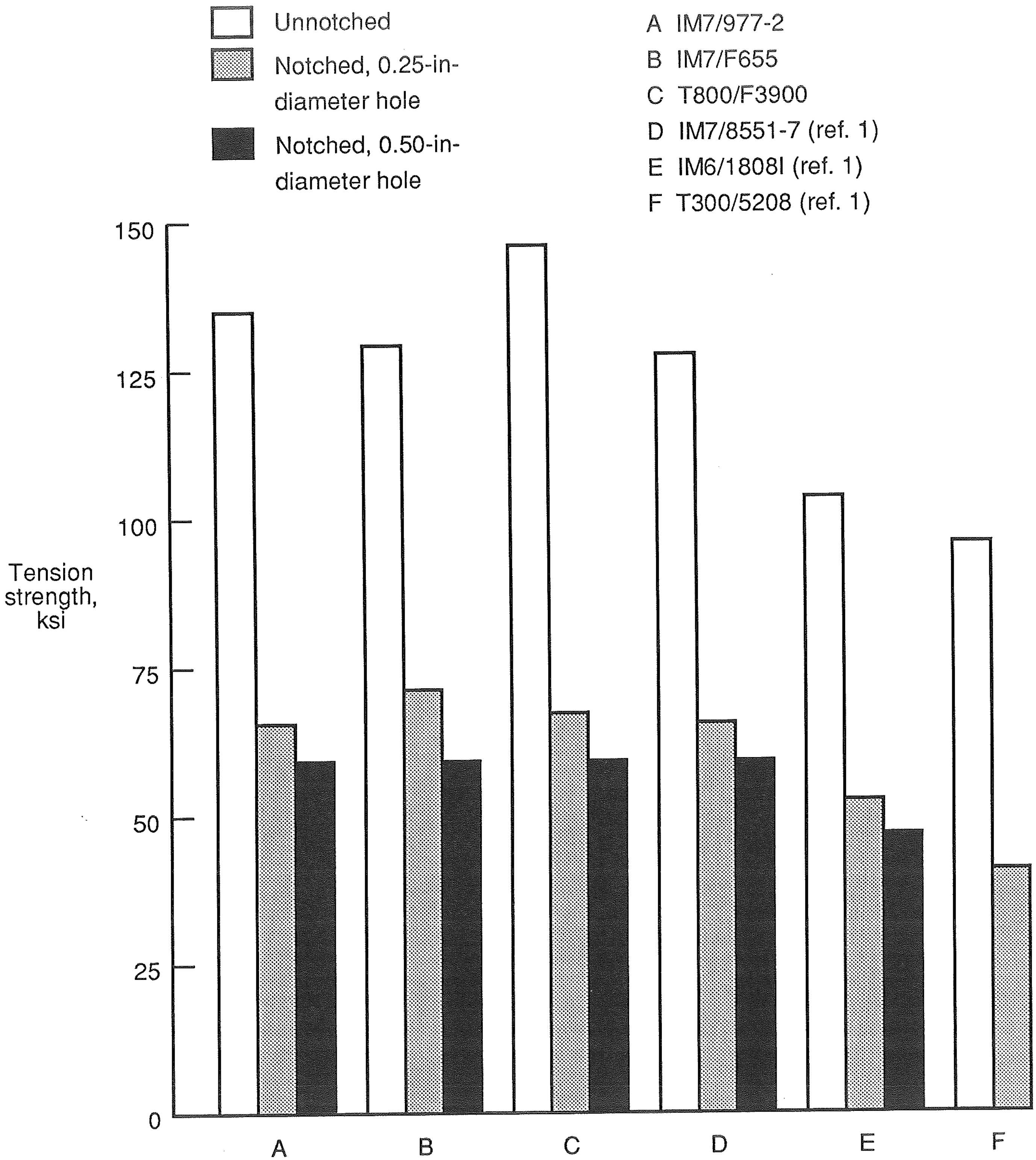


Figure 14. Tension strength for notched and unnotched quasi-isotropic laminates.

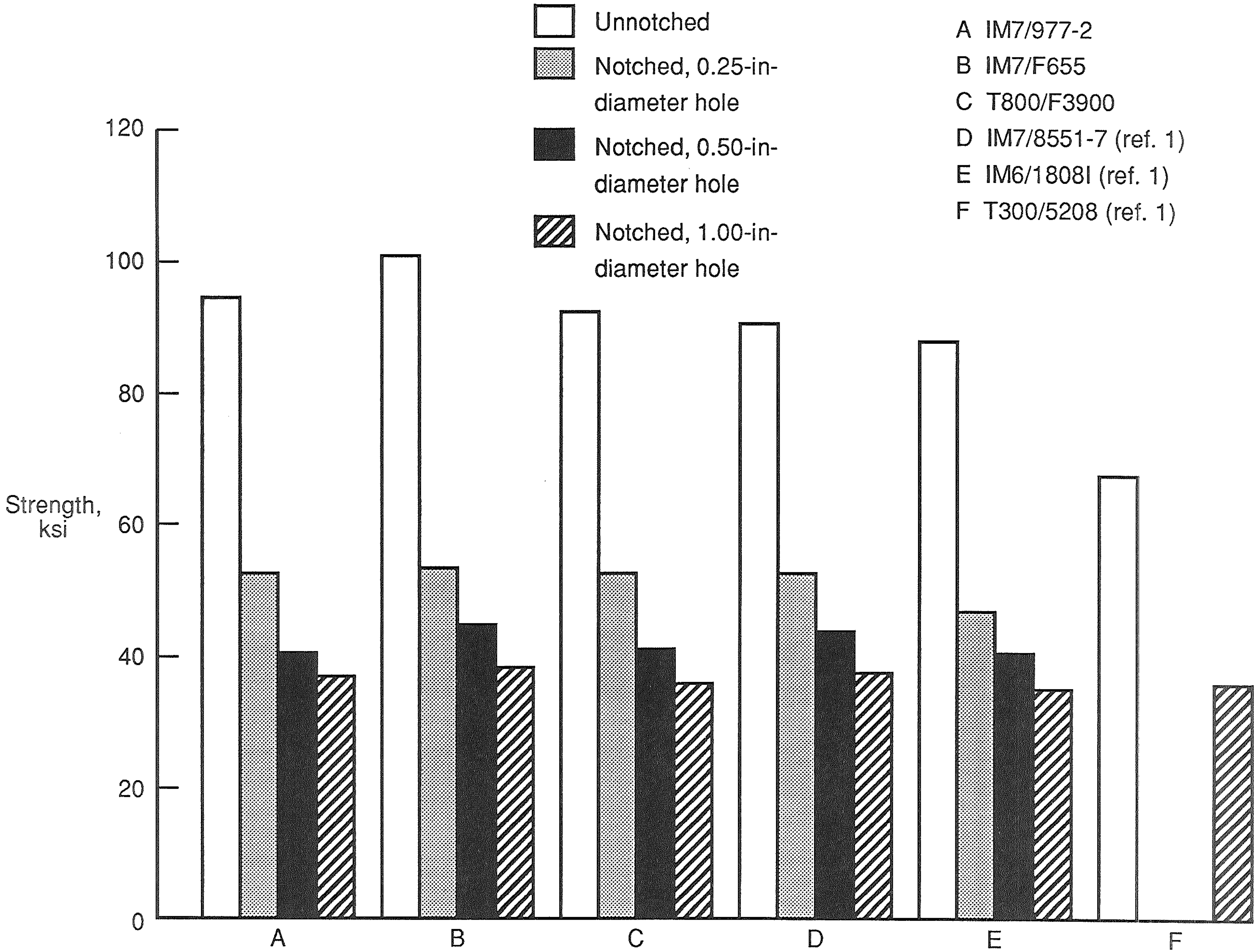


Figure 15. Compression strength for notched and unnotched quasi-isotropic laminates.

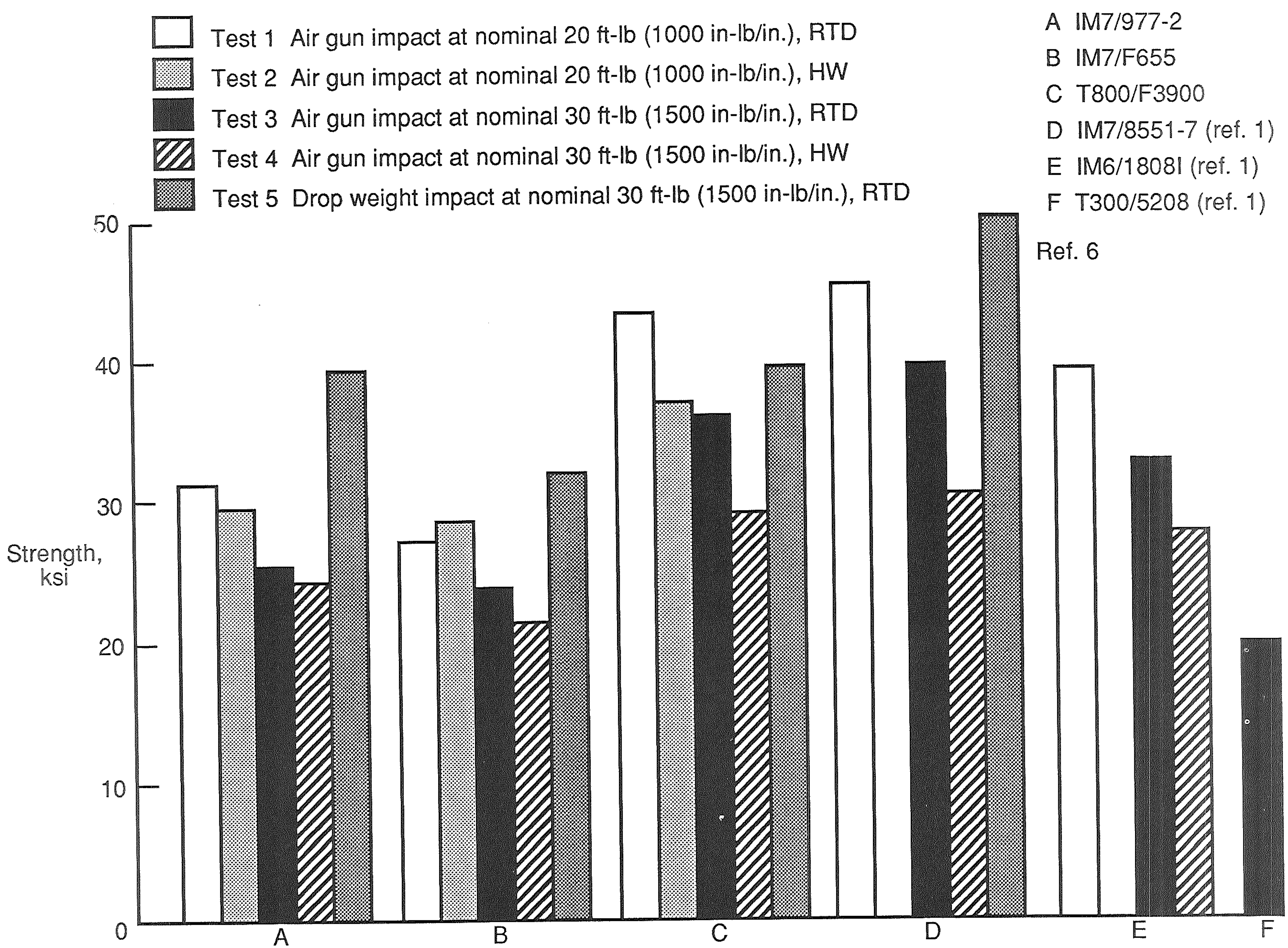
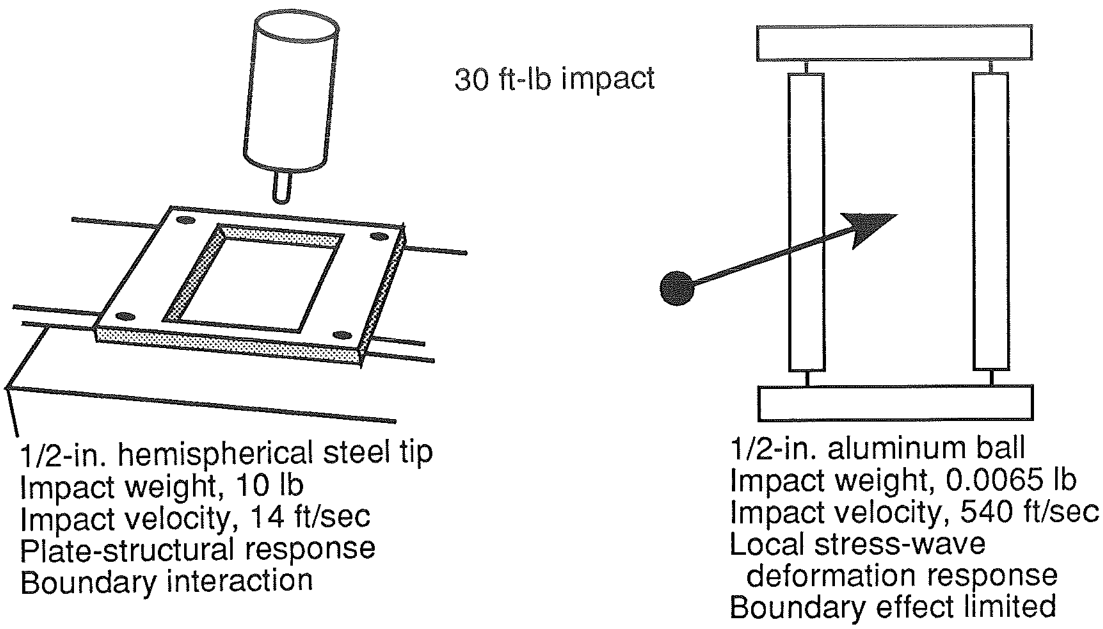
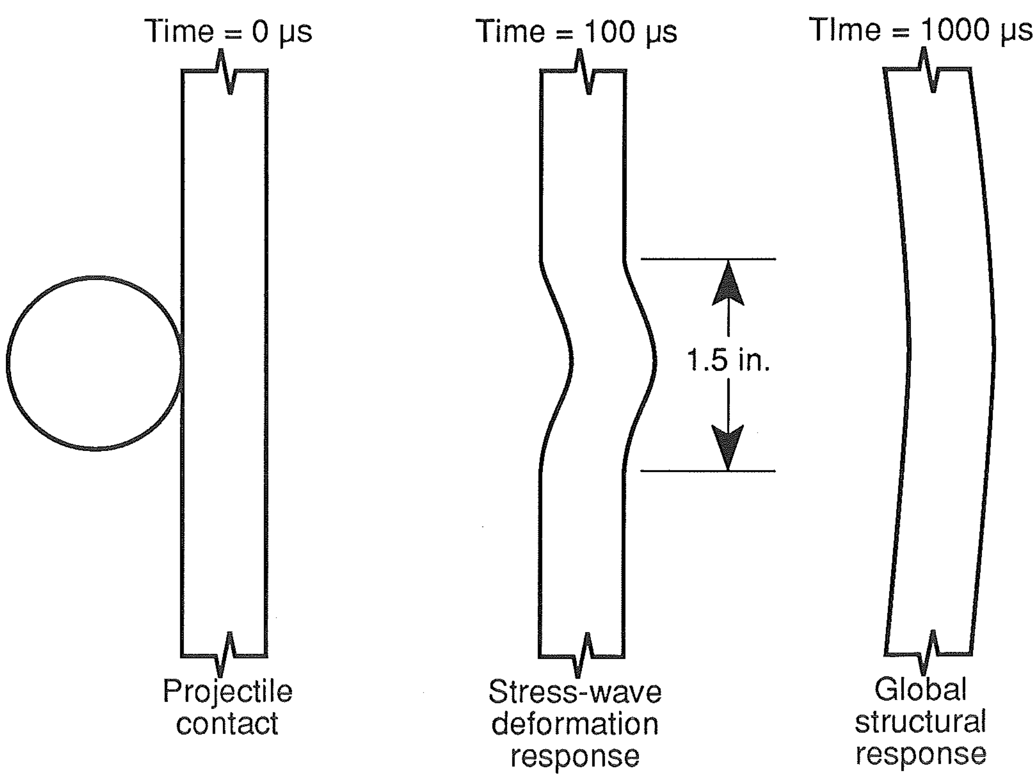


Figure 16. Compression strength for impact-damaged quasi-isotropic laminates.



(a) Impact test methods.



(b) Impact deformation response mechanisms.

Figure 17. Procedures for damaging compression after impact specimens. (From ref. 2.)

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16. Abstract
Results are presented from an experimental evaluation of IM7/977-2, IM7/F655, and T800/F3900. Data presented include ply-level (unidirectional laminate) strengths and moduli, unnotched and notched (open-hole) tension and compression properties of quasi-isotropic laminates, and compression-after-impact strengths. These data are compared with properties of other toughened (IM7/8551-7 and IM6/1808I) and brittle (T300/5208) graphite/epoxy materials. The IM7/977-2, IM7/F655, and T800/F3900 materials are substantially stronger and more damage tolerant than widely used first-generation composite materials such as T300/5208. The T800/F3900 outperforms IM7/977-2 and IM7/F655 materials in tolerance to projectile impacts. Compression-after-impact strengths were found to be dependent on impactor velocity for a given impact energy. The open-hole compression properties of all three materials are degraded by the combination of heat and moisture.

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